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AN INVESTIGATION OF TH
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BACKPACKS LOAD
IN VARIOUS CONFIGURATIO

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In this study, the inertial properties of three, external-frame backpack systems were examined under six loading configurations. Two of the backpacks were developed by the Army and one was a commercially-available product. For each configuration, a 12.00-kg load, consisting of military clothing and equipment, was placed in the packs. The locations of the items were manipulated such that the densest were placed low, high, or in an intermediate position within the pack. In addition, two, 4.56-kg weights were strapped to the top,

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bottom, sides, or front of the pack and tested in combination with the intermediate position of the basic load. The mass, centers of mass, and inertia tensors of each backpack were obtained under each of the six loading configurations. The inertial properties of the backpacks and of the loading configurations were compared with respect to properties which are desirable in a backpacking system.

Preface

This is one of four studies comprising the final report of research performed under Contract Number DAAK60-78-C-0033 with the Individual Protection Laboratory, US Army Natick Research and Development Laboratories, Natick, Massachusetts. The work was formulated and directed by Drs. Carolyn K. Bensel and Richard F. Johnson, Human Factors Group, Individual Protection Laboratory. Dr. Bensel was the contract monitor and Dr. Johnson was the alternate.

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An Investigation of the Inertial Properties of Backpacks Loaded in Various Configurations

Introduction

One of the main goals of biomechanics research is to improve the efficiency of human movement. In situations where an external load is being carried, the inertial characteristics of the load may have a large effect on efficiency of movement. For example, a lighter load is usually easier to carry than a heavier one. This, however, may not always be the case. For example, it may be easier to carry two, 20-lb suitcases, one in each hand, than to carry one, 30-lb suitcase. With the former, even though the total weight is 10 lb more than with the latter, the center of mass of the load will fall in the sagittal plane of the body. Thus, the person may not evidence the substantial change in posture that is required to maintain balance when carrying the single, 30-lb suitcase.

When movements involve rotation, the mass and center of mass (CM) are not the only inertial properties involved. Just as mass is the inertial property representing the resistance to change in linear motion, "moment of inertia," which describes the distribution of the mass about a particular axis of rotation, is the inertial property representing the resistance to change in angular motion.

When quick changes in angular motion are desirable, so is a small moment of inertia. Examples of such quick changes are "hitting the dirt" and making a sudden change in direction while running. A backpack with a relatively large moment of inertia about a given axis would be difficult to set into rotary motion. Likewise it would be difficult to stop the rotation once it had begun.

Because a backpack can be loaded in a wide variety of ways, the soldier or recreational hiker has some control over the inertial properties of a particular backpack. There may also be substantial differences between packs of different design. A thorough investigation into the area of backpack inertial properties has not yet been done. It was the purpose of this study to manipulate the loading configurations of three backpacks of different design and to determine their inertial properties in each configuration.

Basic Mechanical Considerations

To understand the methods used in this study requires some knowledge of rigid body dynamics. Although the reader should refer to any of the many texts on the subject (e.g., Synge & Griffith or Greenwood), this section outlines some of the basic mechanical considerations.

In a parallel, uniform gravitational field, an object's mass and weight are proportional to each other, and its center of mass (CM) and center of gravity (CG) lie at the same point. Since the earth's gravitational field approximates this condition, we can infer an object's mass by weighing it and can locate its CM by determining its CG. Weight and CG, however, are not fundamental quantities, they depend on the presence of a gravitational field.

The inertial properties of a rigid body are its mass, CM, and moments of inertia. A certain moment of inertia is defined relative to an axis, one usually (but not necessarily) through the CM. In a three-dimensional body, an infinite number of axes can be passed through the CM, resulting in an infinite number of moments of inertia. Fortunately, these measurements are related in a regular manner, so that, by specifying only six parameters, the entire inertial system can be described.

For a given set of three orthogonal axes drawn through the CM of the body, these six parameters are as follows (see Figure 1):

I_{xx} - the moment of inertia about the X-axis

I_{yy} - the moment of inertia about the Y-axis

I_{zz} - the moment of inertia about the Z-axis

I_{xy} - the product of inertia with respect to the XZ and YZ planes

I_{xz} - the product of inertia with respect to the XY and YZ planes

I_{yz} - the product of inertia with respect to the XY and XZ planes

These six parameters form a symmetric matrix which is referred to as the "inertia tensor":

$$\begin{bmatrix} I_{xx} & & \\ I_{xy} & I_{yy} & \\ I_{xz} & I_{yz} & I_{zz} \end{bmatrix}$$

[1] Synge, J.L. and B.A. Griffith. Principles of Mechanics. New York, New York: McGraw-Hill, 1942.

[2] Greenwood, D.T. Principles of Dynamics. Englewood Cliffs, New Jersey: Prentice Hall, Inc., 1965, pp. 362-401.

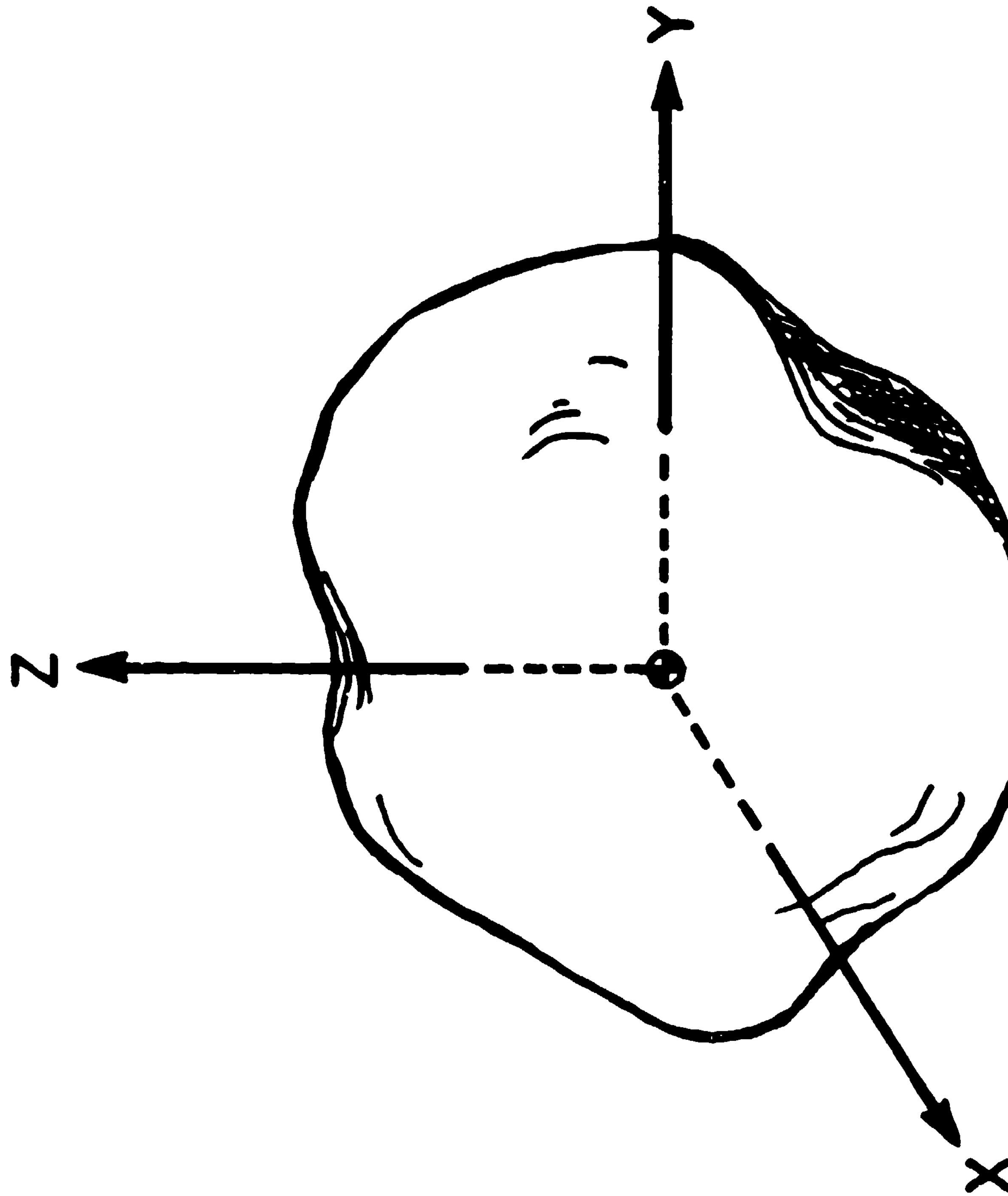

Figure 1. A generalized rigid body showing three orthogonal coordinate axes through the CM.

The diagonal elements are the moments of inertia and the off-diagonal elements are the products of inertia.

If the X, Y, and Z axes chosen are "principal axes of inertia", the products of inertia vanish, and the inertia tensor reduces to its diagonal form.

$$\begin{bmatrix} I_{xx} & & \\ 0 & I_{yy} & \\ 0 & 0 & I_{zz} \end{bmatrix}$$

Conversely, the presence of product terms indicates the principal axes are rotated relative to the coordinate axes. Either way of expressing the inertia tensor, however, requires the specification of six parameters. One can specify either (1) the three moments and three products of inertia for a given axis system, or (2) the three principal moments of inertia and the orientations of the three principal axes of inertia relative to a given axis system.

In order to get an intuitive feeling for the importance of principal moments and axes of inertia, consider a rigid axle with two masses positioned in the X-Y plane as shown in Figure 2. The system rotates about the fixed axle which is coincident with the Y axis. The center of mass lies in the axle. Since the axle could balance in any static position, the system is said to be "statically balanced".

The system is not, however, "dynamically balanced." There is a nonzero product of inertia, I_{yz}, which would produce shear forces tending to pull the axle out of its bearings when rotating. As can be seen in Figure 2, two of the three principal axes (Y' and Z') are displaced from their corresponding coordinate axes by the particular placement of the masses. If the masses were placed one above the other on opposite sides of the axle, I_{yz} would vanish. The system could then rotate about a principal axis of inertia and thus be dynamically balanced. An everyday example of this is a wheel of an automobile. It is important to have the axle of the wheel coincide with a principal axis. This avoids the vibration commonly encountered when driving on a wheel that is not dynamically balanced.

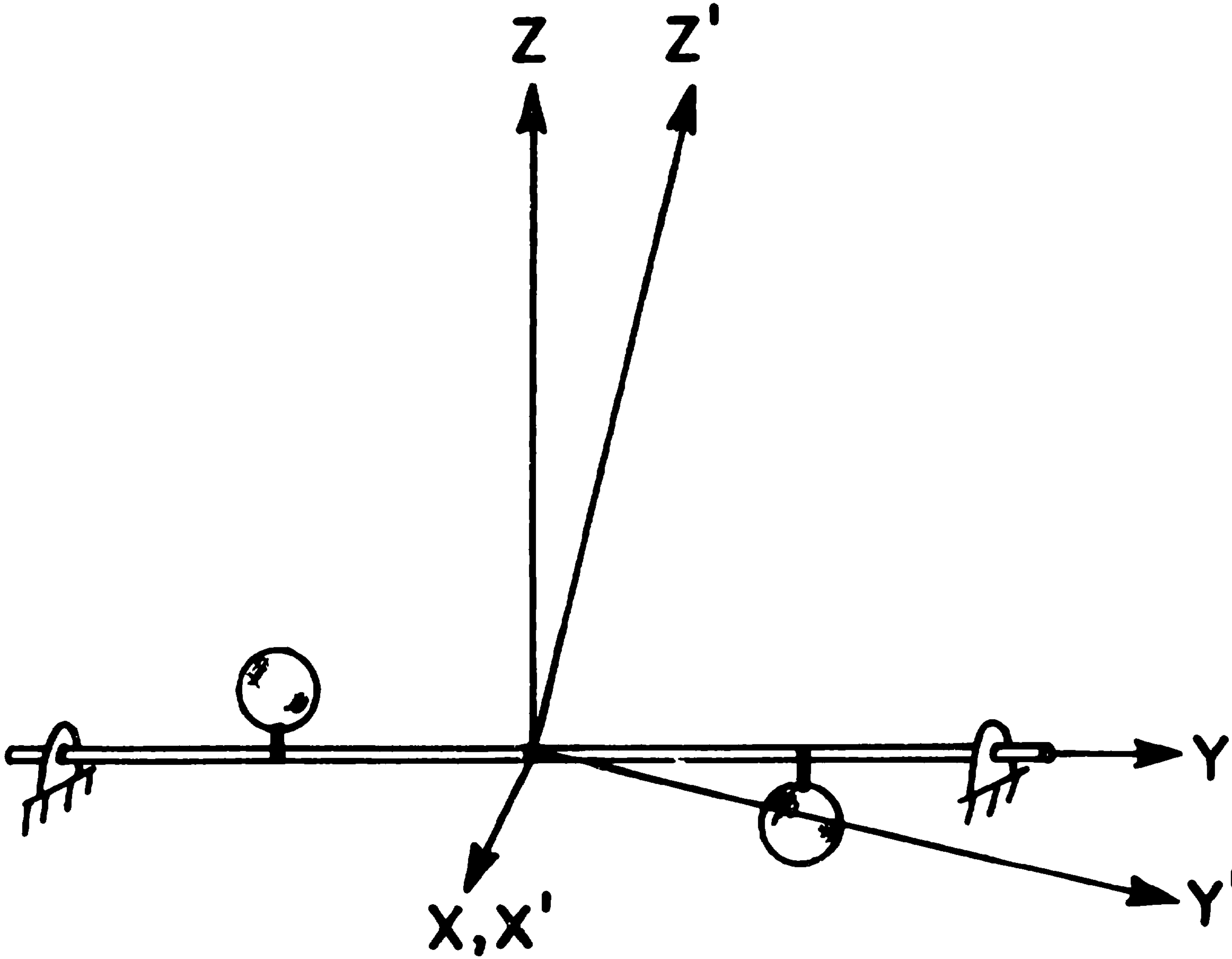

Figure 2. An example of fixed rotation about a non-principal axis of inertia.

Procedures

The calculation of inertial properties requires the use of some fairly sophisticated procedures. In this study, a sensitive balance was used to determine mass, a reaction board was used to determine center of mass, and a pendulum was used to calculate the inertia tensor. The theory underlying these methods will be discussed first followed by a detailed description of the procedures.

Theoretical Basis Underlying the Methodology

Center of mass. Consider the free-body diagram (FBD) of a reaction board apparatus shown in Figure 3. The force measured at one end (B_1) is related to the mass of the board and the location of its CM in the following manner:

$$B_1 = \frac{m_1 \; g \; d_1}{\ell} \qquad (1)$$

where m_1 is the mass of the board, g is the acceleration due to gravity, d_1 is the distance to the CM of the board from the pivot point A, and ℓ is the distance between the points A and B.

Shown in Figure 4 is the FBD of the same apparatus with an object of mass m_2 placed on the board with the projection on the board of its CM at an unknown distance d_2 away from the pivot point A. The force measured at the other end (B_2) reflects the contributions of both the board and the object in the following manner:

$$B_2 = \frac{m_1 \; g \; d_1}{\ell} + \frac{m_2 \; g \; d_2}{\ell} \qquad (2)$$

$$= B_1 + \frac{m_2 \; g \; d_2}{\ell}$$

Solving Equation 2 for the CM distance d_2 yields

$$d_2 = \frac{(B_2 - B_1) \; \ell}{m_2 \; g}$$

If the object is placed on the board in three different ways, the location of its CM in three-dimensional space can be determined.

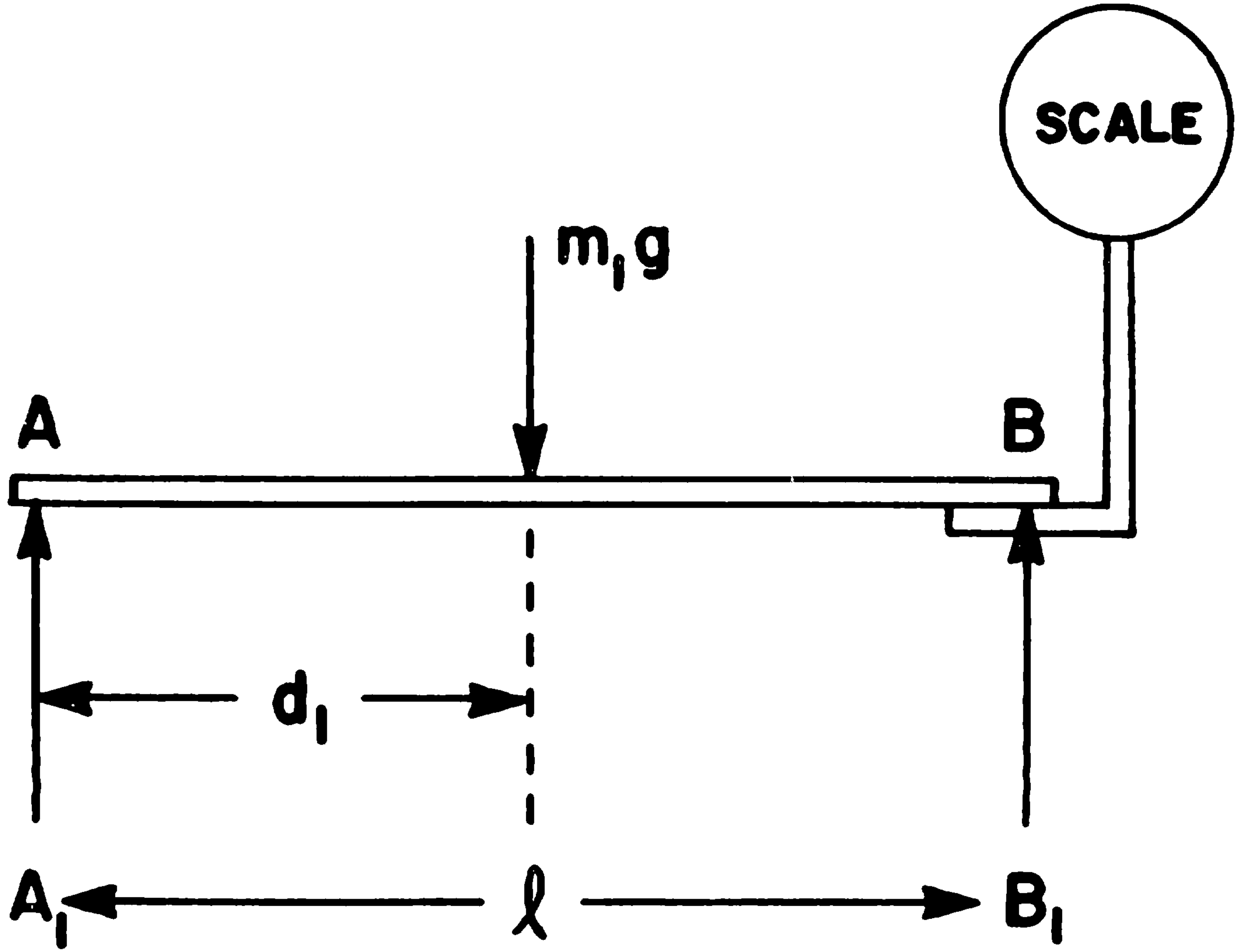

Figure 3. Free body diagram (FBD) of reaction board.

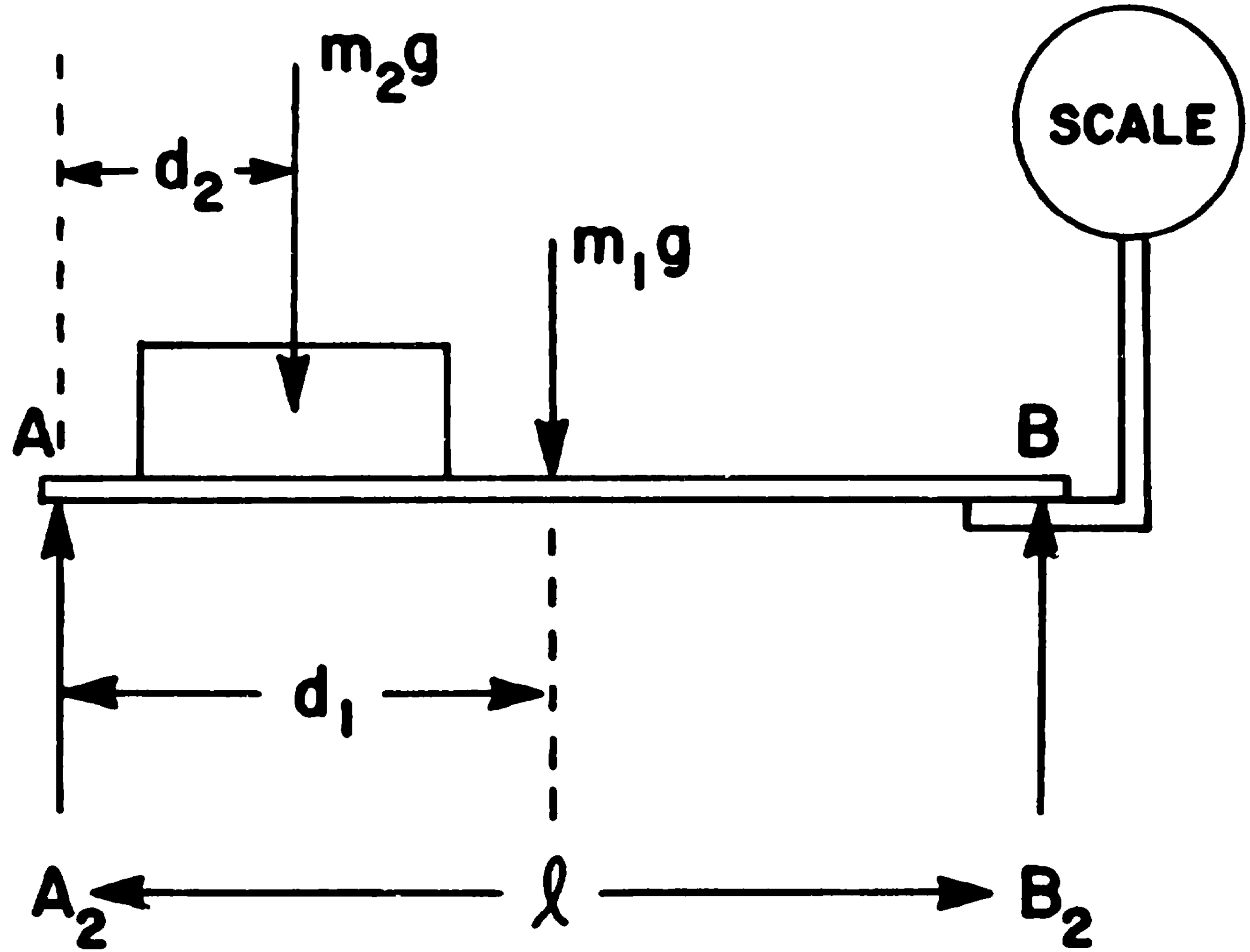

Figure 4. Free body diagram (FBD) of reaction board with an object placed on it.

Inertia tensor. Inertia tensors were determined here using a pendulum technique similar in theory to that described by Chandler et al.[3]

When an object is suspended in a pendulum (see Figure 5) and allowed to oscillate through small angles ($\theta = 5°$), the period of oscillation (T) is related to the mass of the pendulum (m), the effective pendulum length (d - the distance between the swing axis 0 and the pendulum CM), and its moment of inertia about 0 (I^o).

$$T = 2\pi\sqrt{\frac{I^o}{m\ g\ d}} \tag{4}$$

where g is the acceleration due to gravity (9.81 m/sec^2).

Since it is possible to me sure the mass, CM. and period of oscillation of the pendulum, one can solve r the moment of inertia I^o. Rearranging terms in Equation 4 yields

$$I^o = \frac{m\ g\ d\ T^2}{4\pi^2} \tag{5}$$

If the pendulum consists of a composite system (e.g. a backpack fixed inside a rigid holder) then the computed moment of inertia will reflect the contribution of both the pack and its holder. Since the object of concern is the backpack, an additional measurement must be made on the holder alone. Since moments of inertia are additive, the moment of inertia of the pack (about the swing axis 0) is

$$I^o\ (\text{pack}) = I^o\ (\text{composite}) - I^o\ (\text{holder}) \tag{6}$$

One final step is needed to calculate the moment of inertia of the pack about one particular axis through its CM. This involves the parallel axis theorem and is shown in Equation 7.

$$I^{CM}\ (\text{pack}) = I^o\ (\text{pack}) - m_p\ d_p^{\ 2} \tag{7}$$

where m_p is the mass of the pack and d_p is the distance between the swing axis 0 and the parallel axis through the CM of the pack (not the composite).

Combining Equations 5, 6, and 7 yields

$$I^{CM}(\text{pack}) = \frac{m_c\ g\ d_c\ T_c^{\ 2}}{4\pi^2} - \frac{m_h\ g\ d_h\ T_h^{\ 2}}{4\pi^2} - m_p\ d_p^{\ 2} \tag{8}$$

[3]Chandler. R.F.. C.E. Clauser, J.T. McConville, H.M. Reynolds, and J.W. Young. "Investigation of Inertial Properties of the Human Body" (Tech. Rep. AMRL-TR-74-137). Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, 1975. (AD-A016-485)

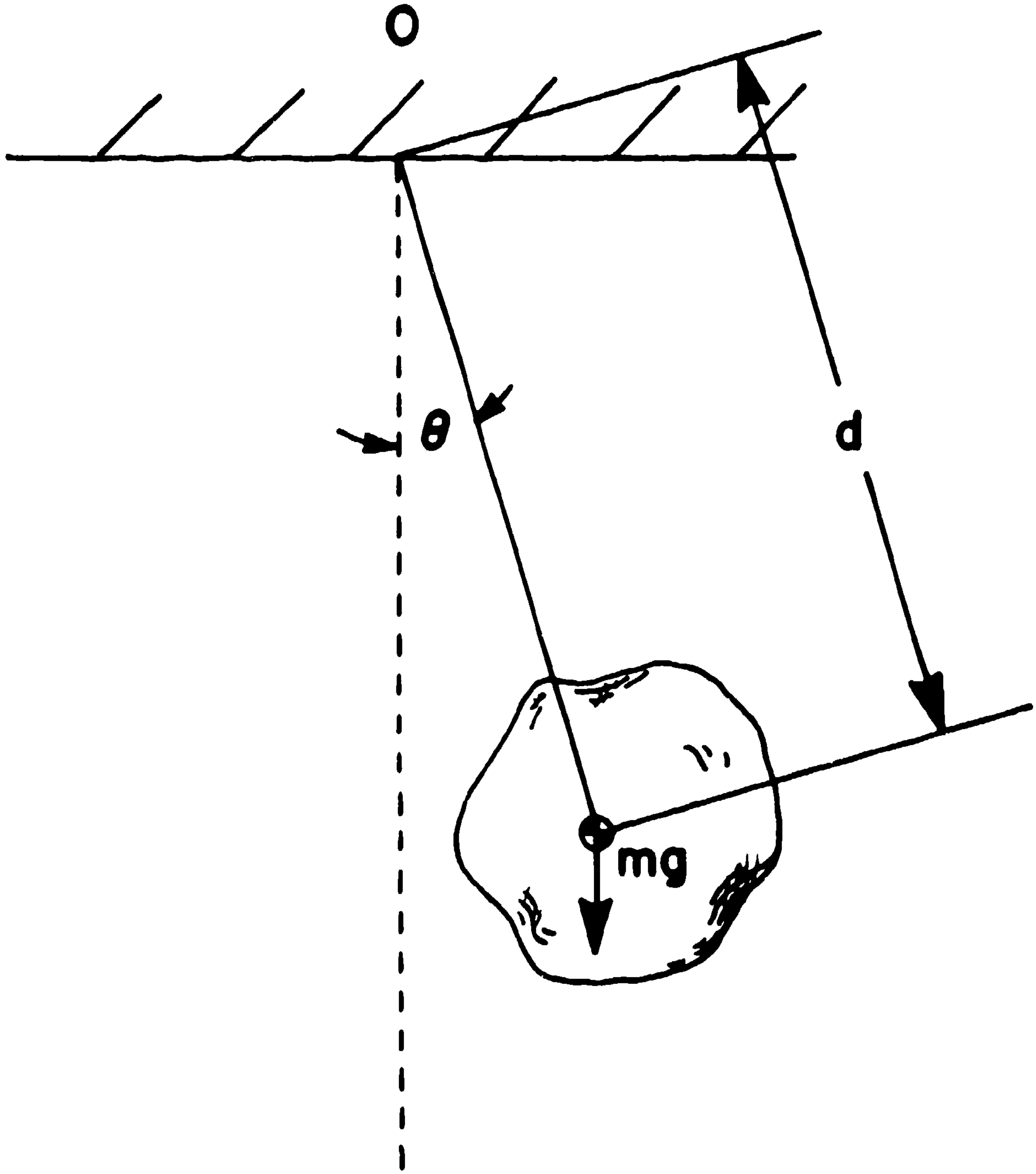

Figure 5. Pendulum system for determination of moments of inertia.

where the subscript c refers to the composite, h refers to the holder, and p refers to the pack.

Three sets of measurements are taken to arrive at the moments of inertia of the backpack about the X, Y, and Z axes (I_{xx}, I_{yy}, and I_{zz}, respectively). The products of inertia (I_{xy}, I_{xz}, and I_{yz}), however, are still unknown. To determine these terms, three additional sets of measurements must be taken about the following axes: (1) an axis in the XY plane nonparallel to either X or Y (the "XY axis"), (2) an axis in the XZ plane nonparallel to either X or Z (the "XZ axis"), and (3) an axis in the YZ plane nonparallel to either Y or Z (the "YZ axis"). If the orientations of these axes are known relative to the coordinate axes, the products of inertia can be computed using the following equations:

$$I_{xy} = \frac{I_{xx} + I_{yy} \tan^2\alpha - (1 + \tan^2\alpha)\, I_{\alpha\alpha}}{2 \tan \alpha} \qquad (9)$$

$$I_{xz} = \frac{I_{xx} + I_{zz} \tan^2\beta - (1 + \tan^2\beta)\, I_{\beta\beta}}{2 \tan \beta} \qquad (10)$$

$$I_{yz} = \frac{I_{yy} + I_{zz} \tan^2\gamma - (1 + \tan^2\gamma)\, I_{\gamma\gamma}}{2 \tan \gamma} \qquad (11)$$

where α is the angle between the X axis and the XY axis, β is the angle between the X axis and the XZ axis, and γ is the angle between the Y axis and the YZ axis. $I_{\alpha\alpha}$, $I_{\beta\beta}$, and $I_{\gamma\gamma}$ are the moments of inertia about the XY, XZ, and YZ axes, respectively.

Backpack Systems

The backpacks selected for this study were three, external-frame systems. Each was tested without its shoulder straps or waist belt. Two of the backpacks were developed by the Army (ALICE and 1956) and one was a commercially-available product. A brief description of each system is included here. Appendix A contains additional information on these items.

a. ALICE. The frame is made of aluminum tubing. It has shoulder straps and a lower back strap made of a cloth spacer material covered with nylon duck. The waist strap is constructed of narrow webbing. The ALICE pack is a top-loading bag with a large main compartment and additional outside pockets.

b. 1956. This frame is also made of aluminum tubing. It is contoured such that the frame is concave relative to the wearer's back. This frame was outfitted with the ALICE pack.

c. Commercial. The aluminum frame of the Camp Trails Astral Model is comprised of two vertical and three horizontal components. The shoulder straps and waste band are padded. The nylon pack contains two internal and five external compartments.

Loading Configurations

Army clothing and equipment constituted a 12.00-kg load which was put in the main compartments of each pack. Further information on the components of this basic load is presented in Appendix A. The particular items used and their individual weights are as follows:

	Item	Weight (kg)
1.	Mattress	1.32
2.	Overshoes, 1 pair	2.31
3.	Poncho	1.29
4.	Waterproof clothes bag	.15
5.	Sleeping bag	3.08
6.	Field coat with liner	1.93
7.	Field trousers with liner	1.18
8.	Cold weather underwear	.60
9.	Socks, 1 pair	.08
10.	Handkerchief	.02
11.	Washcloth	.04

Two, 4.56-kg weights were also used to simulate additional items, such as ammunition, which might be placed in outside pockets on a pack or strapped to some portion of the outside of a pack.

Each backpack was tested under six loading configurations (L.C.). Two configurations consisted of all the items comprising the basic 12.00-kg load; four configurations consisted of the items in the basic load plus the two, 4.56-kg weights. The six loading configurations were as follows:

L.C. 1. Basic load low - no weights
L.C. 2. Basic load high - no weights
L.C. 3. Basic load intermediate - both weights on bottom of pack
L.C. 4. Basic load intermediate - both weights on top of pack
L.C. 5. Basic load intermediate - one weight on each side of pack
L.C. 6. Basic load intermediate - both weights on front of pack

Configurations of basic load. In order to establish the low, intermediate, and high placements of the basic load within the packs, subjective judgments were made of the densities of the 11 items of clothing and equipment which comprised the load. Since most of the items are compressible, actual measurement of their densities requires that a determination be made of the volume that each item occupies within the pack. This was not feasible. Thus, subjective judgments of densities were made.

For the low load configuration (L.C. 1), the items were placed in the packs in order of decreasing density with the densest item (1-mattress) on the bottom and the least dense item (11 - washcloth) on the top. Therefore, the clothing and equipment was ordered from 1 (bottom) through 11 (top). For the high load configuration (L.C. 2), this order was reversed; the least dense item (11) was on the bottom and the densest (1) was on the top. Therefore, the clothing and equipment was ordered from 11 (bottom) through 1 (top). The positioning of the clothing and equipment for the intermediate configurations (L.C. 3-6) varied somewhat among the packs. For the ALICE and the

1956 backpacks, the order of the items, from the bottom to the top of the pack, was as follows: 5, 1, 3, 7, 8, 9, 10, 11, 4, 2, 6. It was necessary to modify this order for the Commercial backpack because, unlike the Army pack which had one main compartment, the Commercial pack had two separate compartments, and the lower of these two could not accomodate the sleeping bag (Item 5). The order in which the items were put into the Commercial pack was as follows:

Lower compartment, bottom to top - 1, 3, 7
Upper compartment, bottom to top - 5, 8, 9, 10, 11, 4, 2, 6

Configurations of added weights. The two extra weights, totalling 9.12 kg, were used in L.C. 3 through 6. They were attached firmly with shoelaces to the outside of the packs to create extreme loading conditions. For L.C. 3 and L.C. 4, the weights were taped together and centered on the bottom and the top of the pack, respectively. These two configurations are pictured in Figures 6 and 7. For L.C. 5, one weight was attached to the approximate center of each side of the pack (Figure 8), while, for L.C. 6, both weights were attached to the front of the packs (Figure 9).

Backpack Holders

Figures 6 to 9 show the backpacks inside their respective aluminum holders. The holders provided the rigidity necessary for testing the packs. Figure 10 shows the holders used for the 1956 and the Commercial packs. The same holder used for the 1956 was used for the ALICE with one modification; a crossbar was added to secure the top portion of the ALICE frame. The dimensions and mass of each holder are listed in Table 1.

Table 1

Dimensions and Mass of the Backpack Holders

Holder	Dimensions (m)			Mass (kg)
	x	y	z	
ALICE	.408	.459	.565	3.865
1956	.408	.459	.565	3.583
Commercial	.330	.561	.921	6.735

Coordinate Axes System

A set of three orthogonal coordinate axes was defined relative to each holder. These axes are drawn schematically in Figure 11. The origin is at the geometric center of the holder. The X axis goes from back to front, the Y axis goes from side to side (right to left) and the Z axis goes from bottom to top.

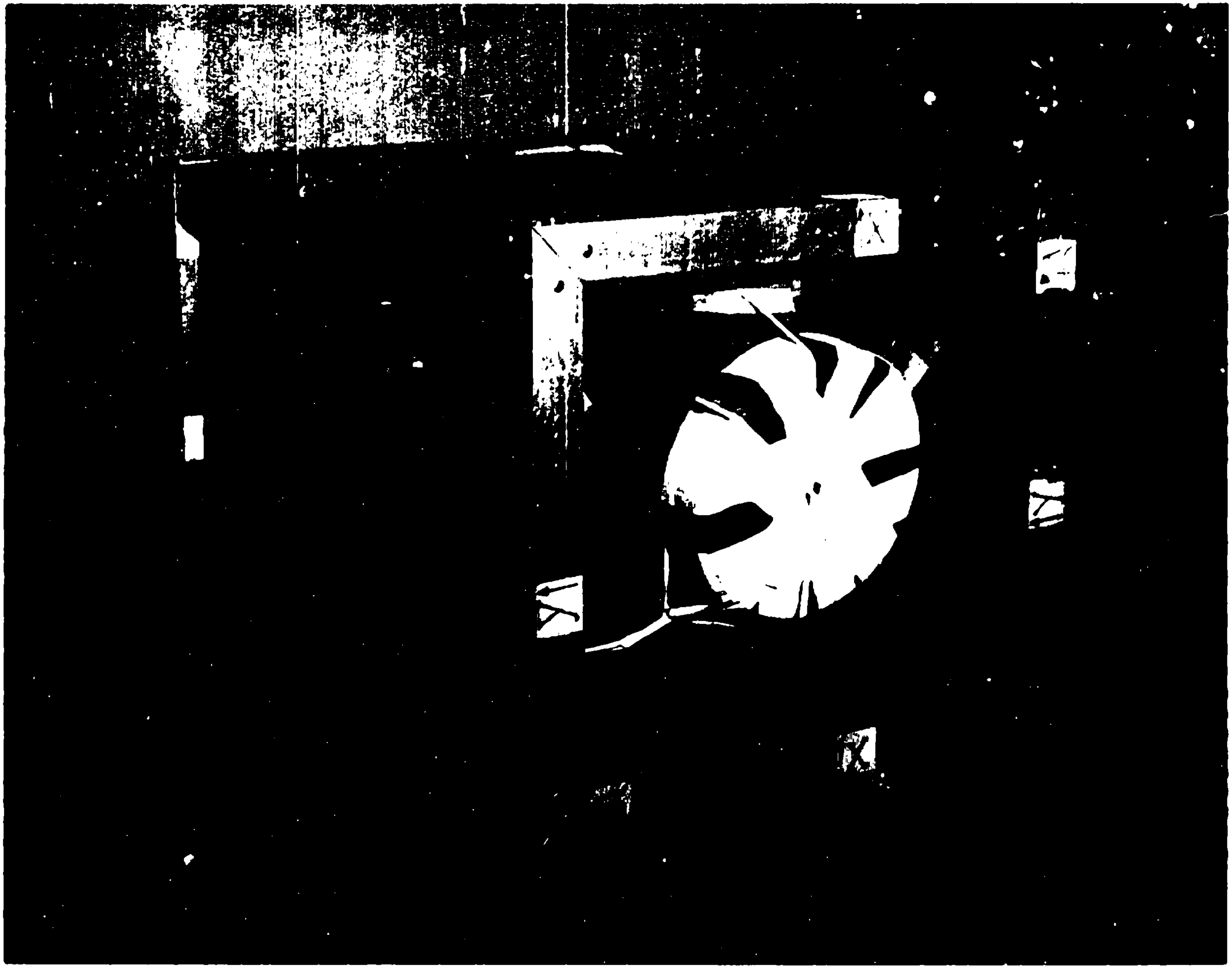

Figure 6. Alice backpack with weights attached to bottom (L.C. 3).

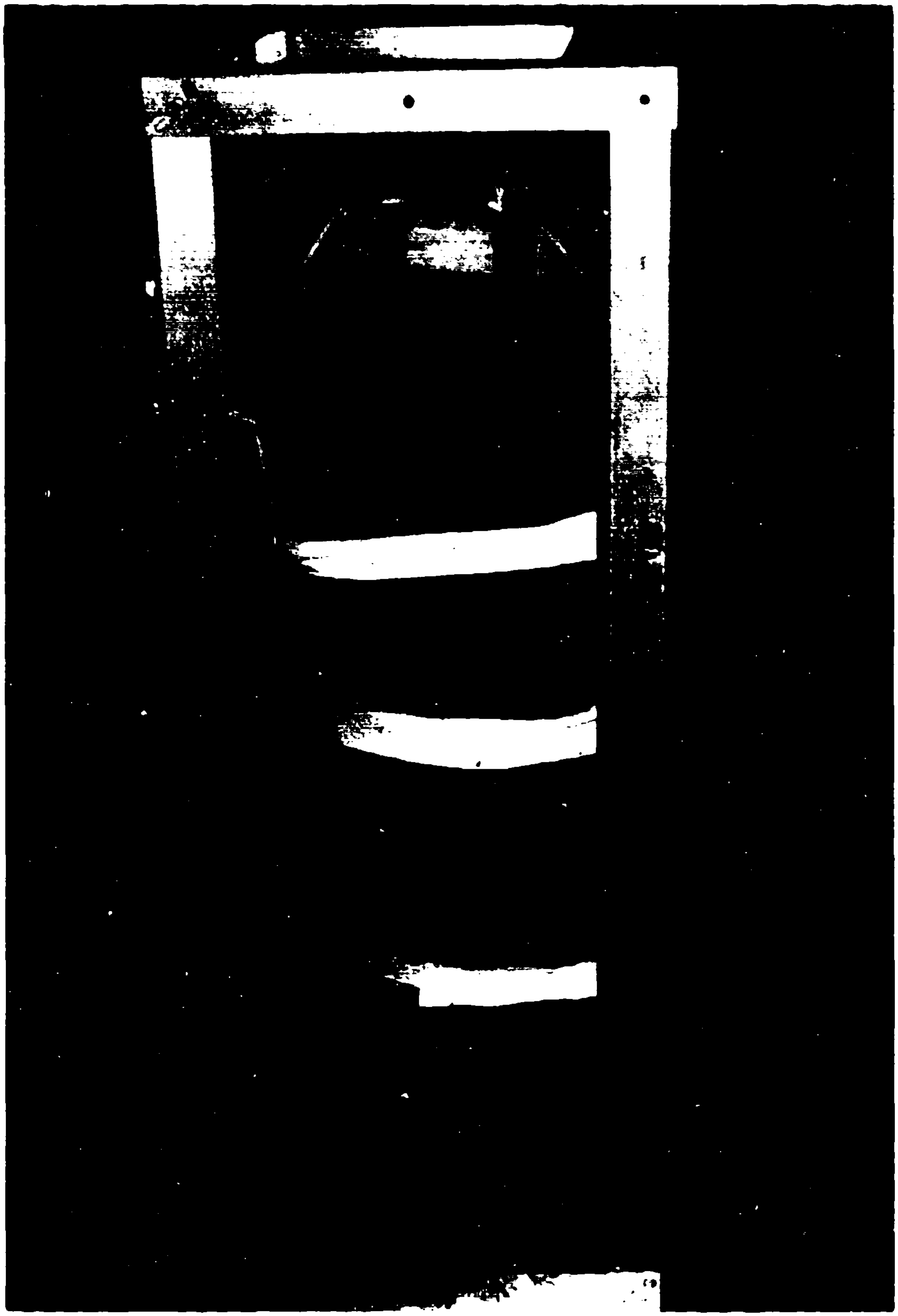

Figure 7. Commercial backpack with weights attached to top (L.C. 4).

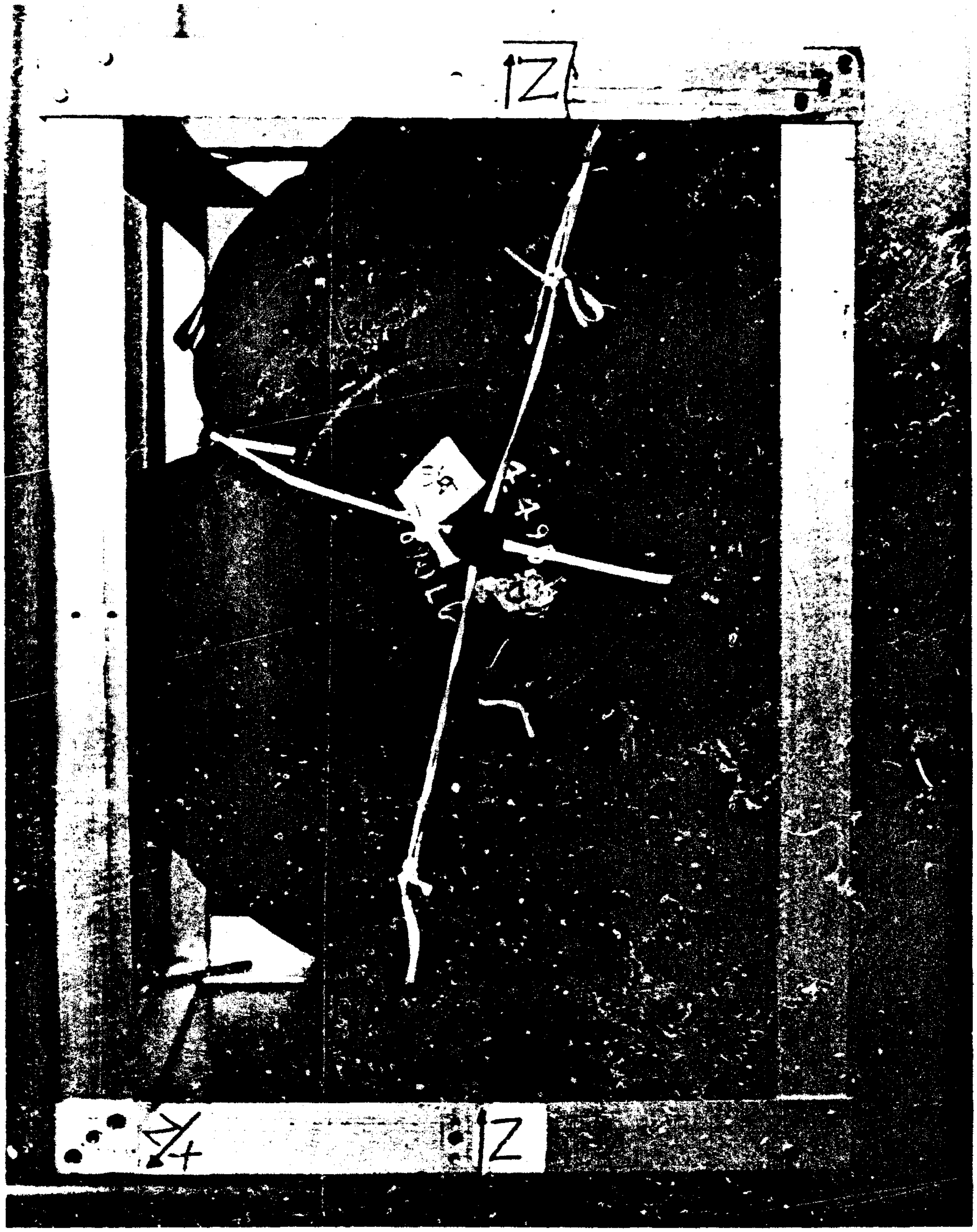

Figure 8. 1956 backpack with one weight attached to each side (L.C. 5).

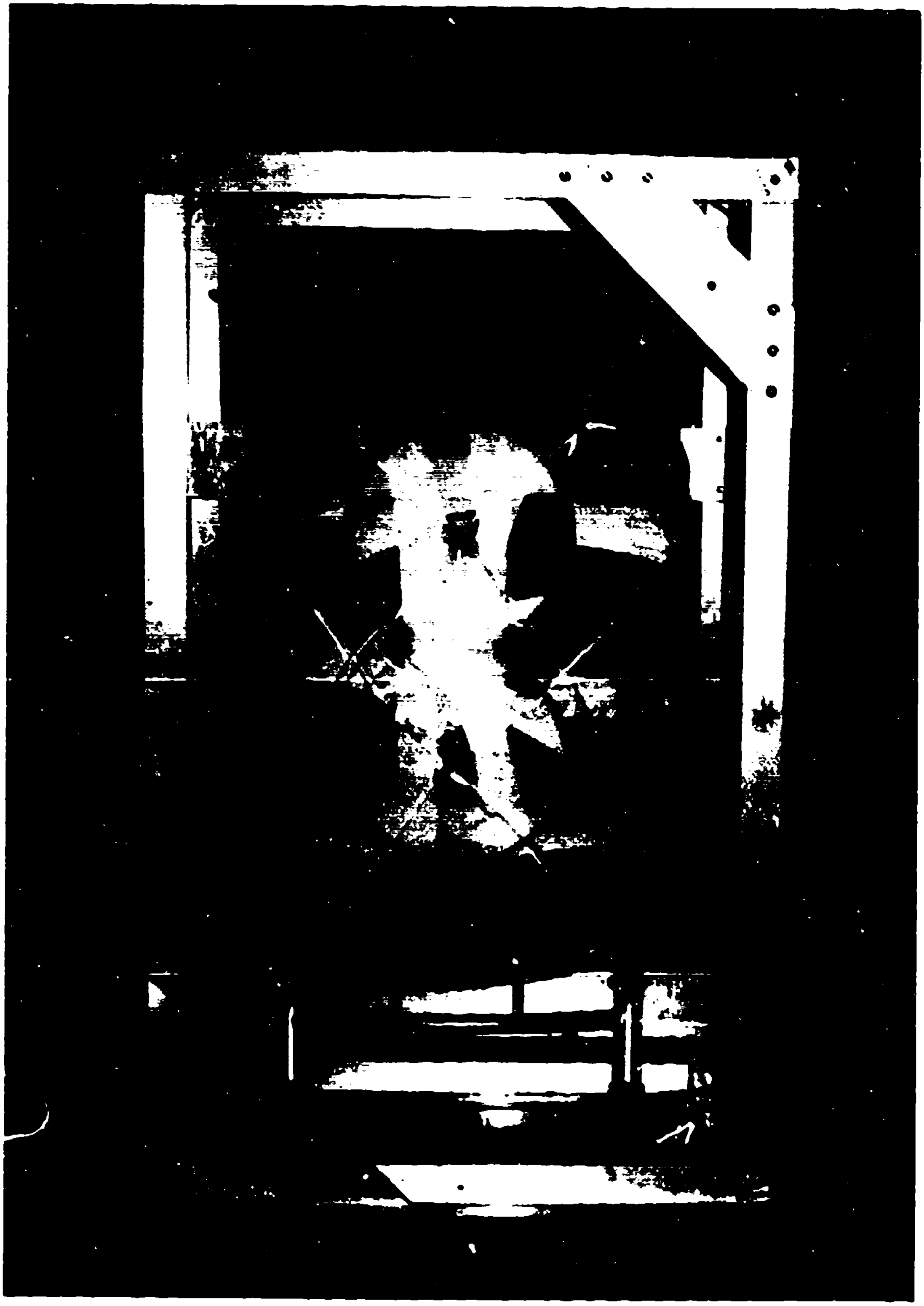

Figure 9. Commercial backpack with weights attached to front (L.C. 6).

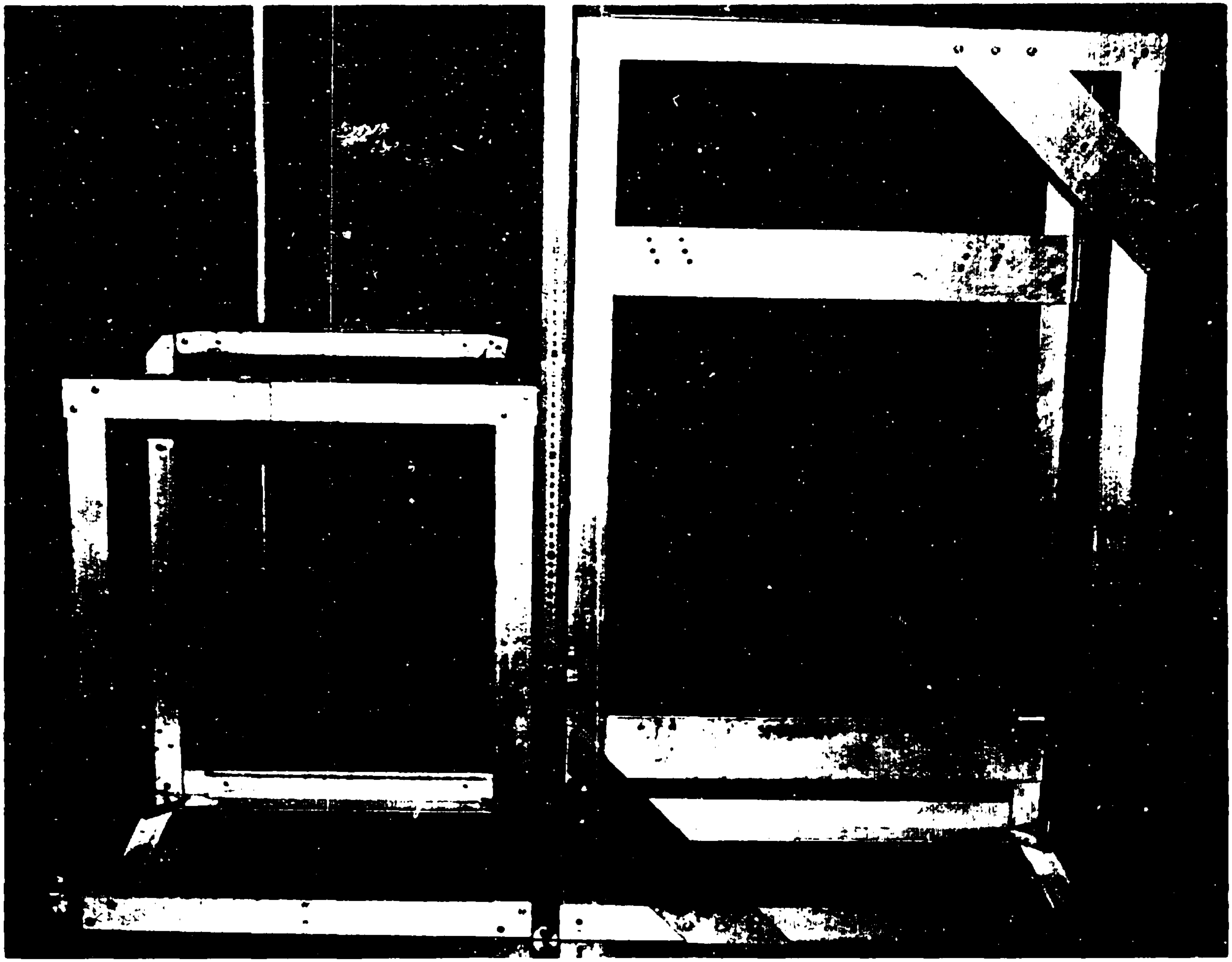

Figure 10. 1956 and Commercial holders shown relative to 1-m stick.

The three nonparallel axes were defined approximately along the face diagonals of the holder. These are also shown in Figure 11 along with the angles defining their orientations. The values of these angles for each holder are listed in Table 2.

Table 2

Diagonal Axes Orientations for the Three Holders

Holder	α	β (degrees)	γ
ALICE	48.7	55.1	51.7
1956	48.7	55.1	51.7
Commercial	60.8	71.8	59.4

Mass Determination

A two-pan balance was used to measure the mass of each holder and of each composite, that is, each backpack in its holder. The balance is shown in Figures 12 and 13. Mass could be measured to the nearest gram. From repeated measurements, however, the accuracy was judged to be within 10 grams. The mass of the backpack was calculated by subtracting the mass of the holder from the mass of the composite.

Center of Mass Determination

The reaction board used to locate the CM of each holder and each composite is shown in Figure 14. The board consisted of a piece of 3/4-inch plywood supported by the points of two wood screws on the left (which defined the "zero line") and the point of a third wood screw at the other end of the board, 110 cm away. This point was placed over one pan of the balance for measurement. The board was leveled by adjusting each screw.

The following describes the protocol used to obtain the three components of the CM of each composite. (The holders were measured in the same way to determine their CM locations.)

Six measurements were taken: two to determine the X component of the CM, two for the Y, and two for the Z. The composite was first placed with the edge of the holder on a line drawn 10 cm to the right of the "zero line" and the positive Y direction pointing towards the balance. After the X distance from the edge of the holder to the CM was calculated, the composite was rotated 180° so that the positive X direction pointed away from the balance. The X distance from the opposite edge of the holder to the CM was then determined.

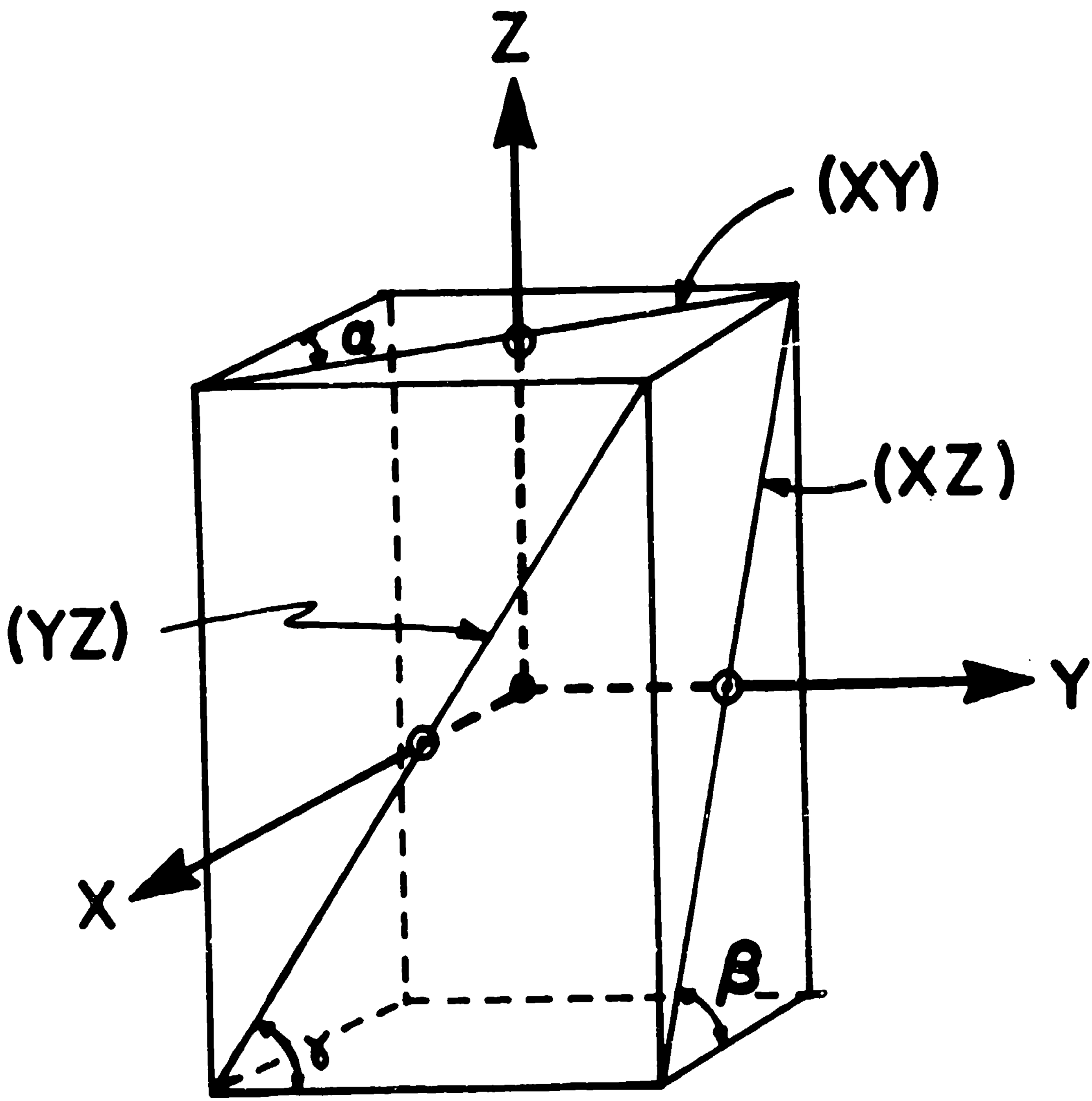

Figure 11. Schematic diagram of holder showing three coordinate axes (X, Y, and Z), three diagonal axes (XY, XZ, and YZ), and their orientation angles (α, β, and γ).

The sum of these two distances should, theoretically, equal the extent of the holder in the X direction, as they are both predicting the location of the same point. The deviation of the actual sum from the theoretical was used as an indicator of the accuracy of the measurement. The two measurements will, in general, not predict the same location due to possible errors arising in the measurement process. The X component of the CM was considered to be the average of the first and second measurements and was expressed relative to the geometric center of the holder.

In a similar fashion, the measurements were repeated to determine the Y and Z components of the CM. Figure 14 shows the ALICE composite being measured for the Z component. The loading configuration of the pack consists of the basic load in the intermediate position and both 4.56-kg weights on the bottom of the pack (L.C. 3).

The accuracy of measurement referred to above was found to be very good; the average deviation in each direction was 1.5 mm for the composites. For the holders, however, the deviation was considerably more, averaging 7 mm for the ALICE and 1956 holders, and 4 mm for the Commercial holder.

It appears that the reaction board was very accurate for determining the CM of relatively heavy items, the composites ranging from roughly 18 to 30 kg, but not as accurate for the lighter holders (3.5 to 6.7 kg). Perhaps a lighter, more delicate reaction board should be used in future work to measure the lighter items.

For each load condition, the CM of each backpack without its holder was calculated by the following equations:

$$x_p = (m_c x_c - m_h x_h) / m_p \tag{12}$$

$$y_p = (m_c y_c - m_h y_h) / m_p \tag{13}$$

$$z_p = (m_c z_c - m_h z_h) / m_p \tag{14}$$

where the subscripts p, c, and h refer to the pack, composite, and holder, respectively; x, y, and z are the three components of CM, and m is mass.

Determination of Inertia Tensor

The oscillation apparatus used to determine the inertia tensor is shown in Figure 15. The apparatus consisted of a rigid stand from which an aluminum rod was attached which served as a fixed axle. A "hinge bar" was attached to the axle with hinge-type joints at each end, allowing nearly frictionless rotation about the axle. This was used to firmly attach the holder or composite to the apparatus for oscillation. This hinge bar became an integral part of the holder or composite being tested, and thus its mass and CM were measured and taken into account in the calculations.

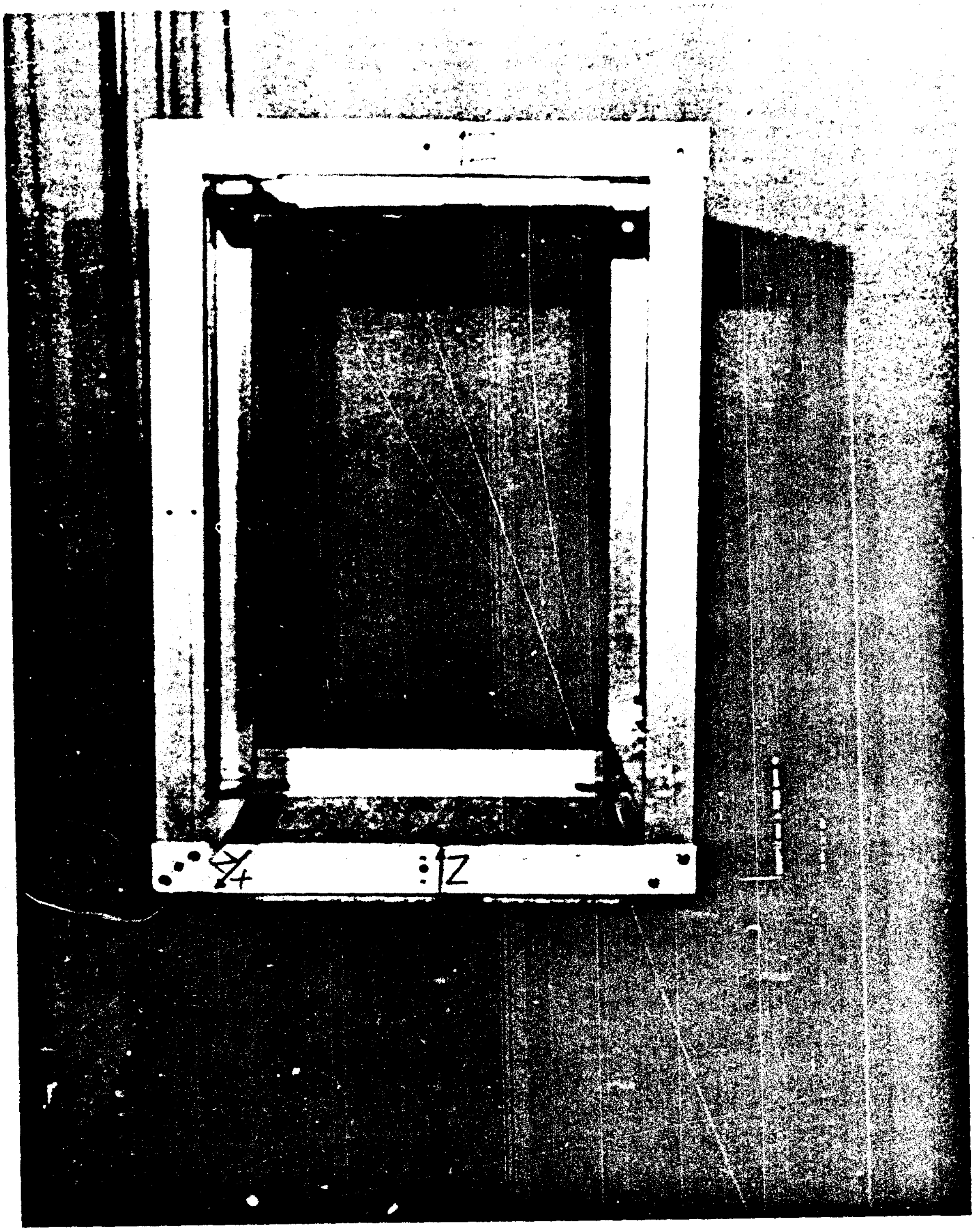

Figure 12. 1956 holder being weighed on balance.

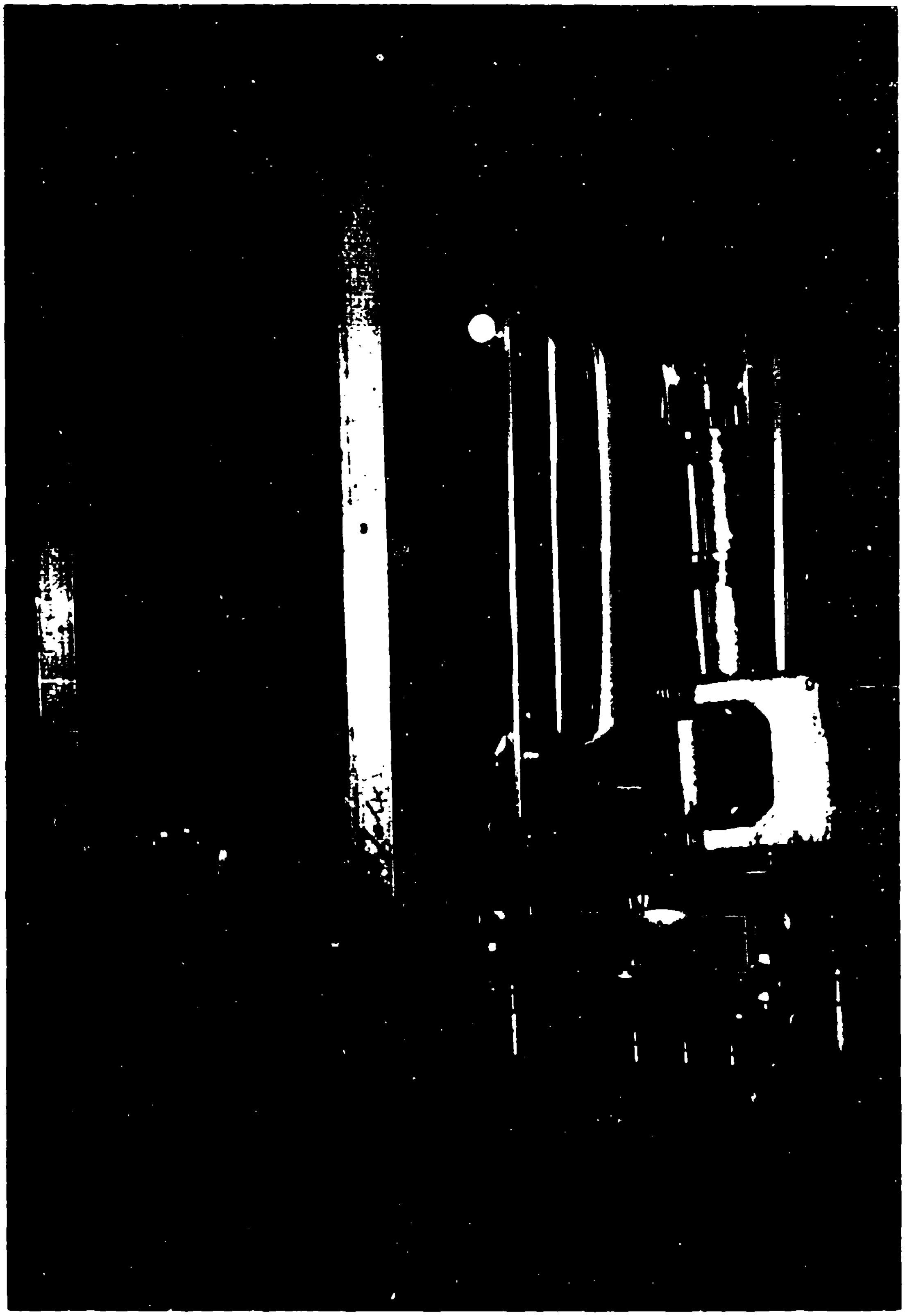

Figure 13. Commercial composite (L.C. 1) being weighed on balance.

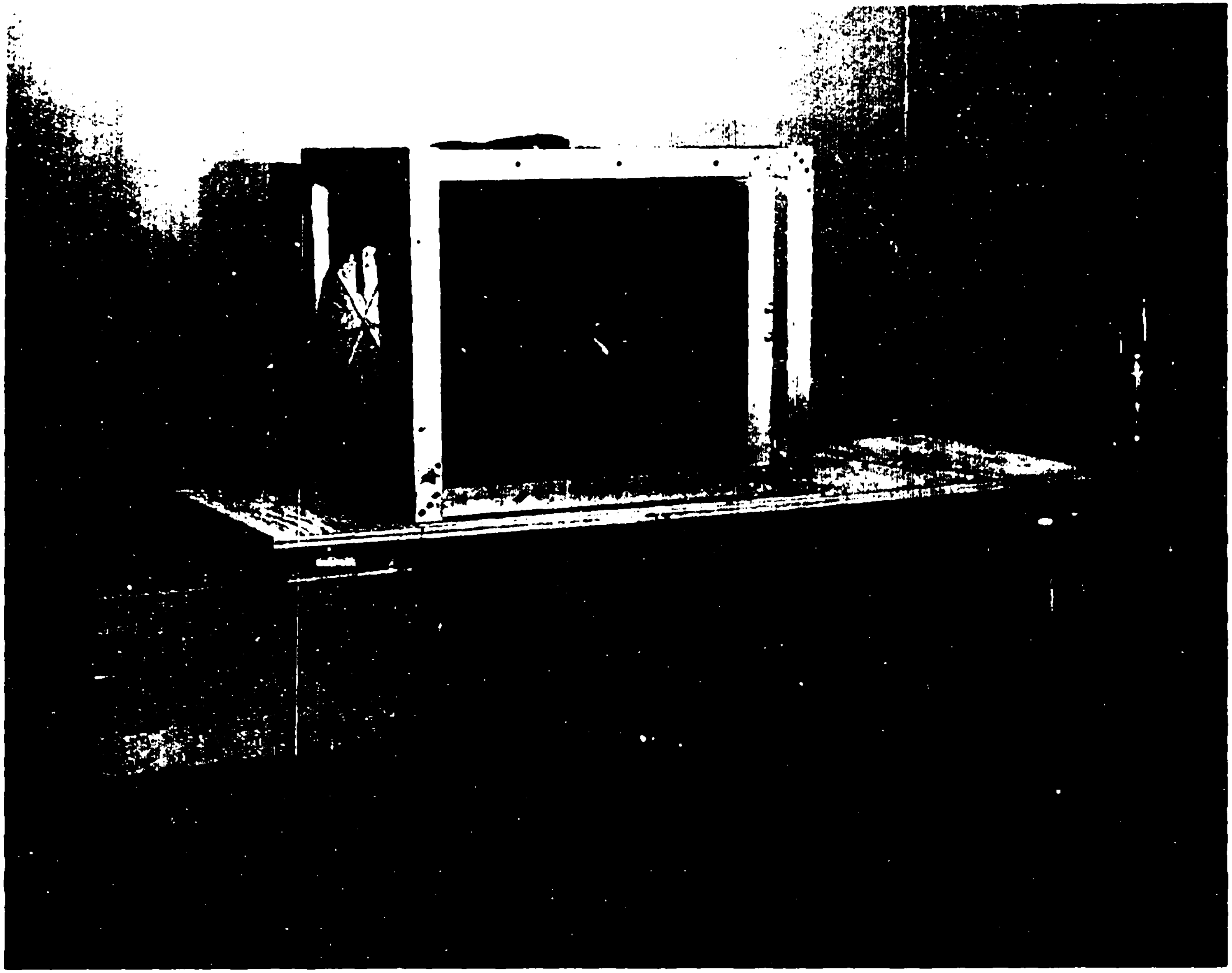

Figure 14. Reaction board apparatus set up to determine Z component of CM of ALICE composite (L.C. 3).

Holes were drilled in the holders to define the six axes of oscillation and to provide means of attaching the holder to the hinge bar with two bolts. Figure 16 shows the 1956 holder suspended for measurement about the YZ axis.

The period of oscillation was measured with a Hewlett Packard digital counter. It was electronically triggered in the following manner:

A thin wooden piece weighing approximately 10 g was placed on the holder. It extended down to within a few cm of the floor. A light was projected on a box containing three photocells placed 5.5 cm apart (see Figure 17). When the pendulum was set into oscillation, the photocells pulsed each time the light was broken by the wooden extension. When the oscillation died down enough so that the light to the outer photocells was no longer interrupted (this represented an angular displacement of approximately 3° from the vertical), the counter was triggered to start the next time the extension passed the central photocell. The counting was automatically stopped exactly 10 cycles later when the extension passed the central photocell.

This procedure was repeated three times, and the average period was obtained over 30 cycles. The three measurements rarely differed by more than 2 msec (in 10 cycles). Thus, the measurement of the period of one cycle was judged to be accurate to within 2×10^{-4} seconds.

A computer program was used to calculate the six effective pendulum lengths and the moments and products of inertia from the data for each holder and each composite (mass, CM, and periods of oscillation about the six axes). This program is included in Appendix B.

<u>Error Analysis and Validation</u>

The inertial-measuring system was evaluated by measuring the inertia tensor of a piece of steel I-beam, cut to have approximately the same mass as the backpacks. Two pieces of angle iron were added to the 1956 holder to accommodate the I-beam and firmly mount it in the holder. The holder and the I-beam are shown in Figure 18 and 19.

The I-beam was carefully measured and weighed. Its mass was 21.093 kg. Although the beam was not found to be perfectly regular, the average dimensions are shown in Figure 20. These dimensions were used to mathematically model the beam as three uniform segments, each a rectangular parallelpiped. The inertia tensor of such a geometric solid has the components $I_{xx} = .7963\ \mathrm{kg\cdot m^2}$, $I_{yy} = .4837\ \mathrm{kg\cdot m^2}$, $I_{zz} = .3739\ \mathrm{kg\cdot m^2}$ with $I_{xy} = I_{xz} = I_{xz} = I_{yz} = 0$. The coordinate axes are shown in Figure 20.

The beam was tested in the same manner as previously described for the backpacks. The results and the deviations from the theoretical values are shown in Table 3.

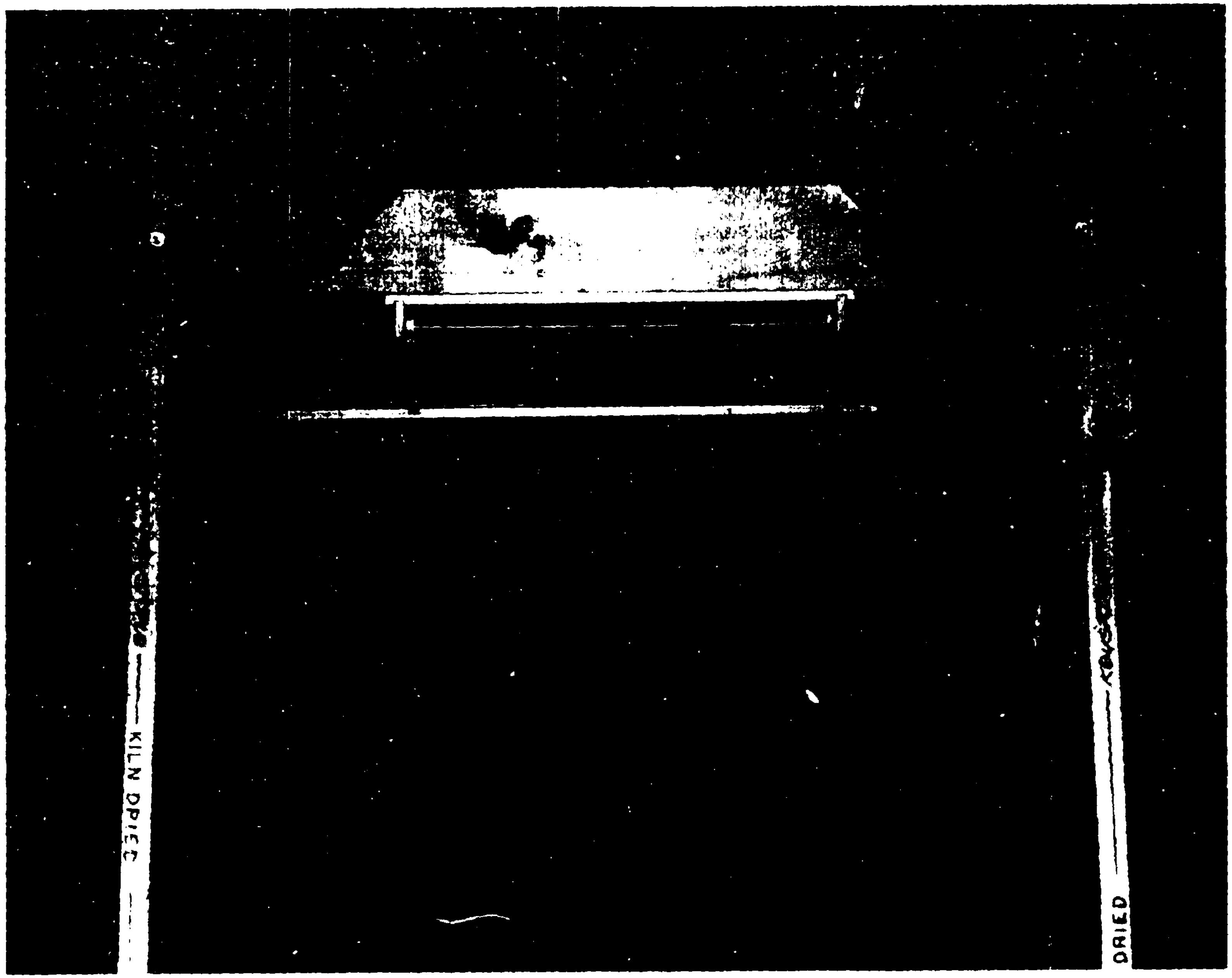

Figure 15. Oscillation stand from which holders and composites were swung.

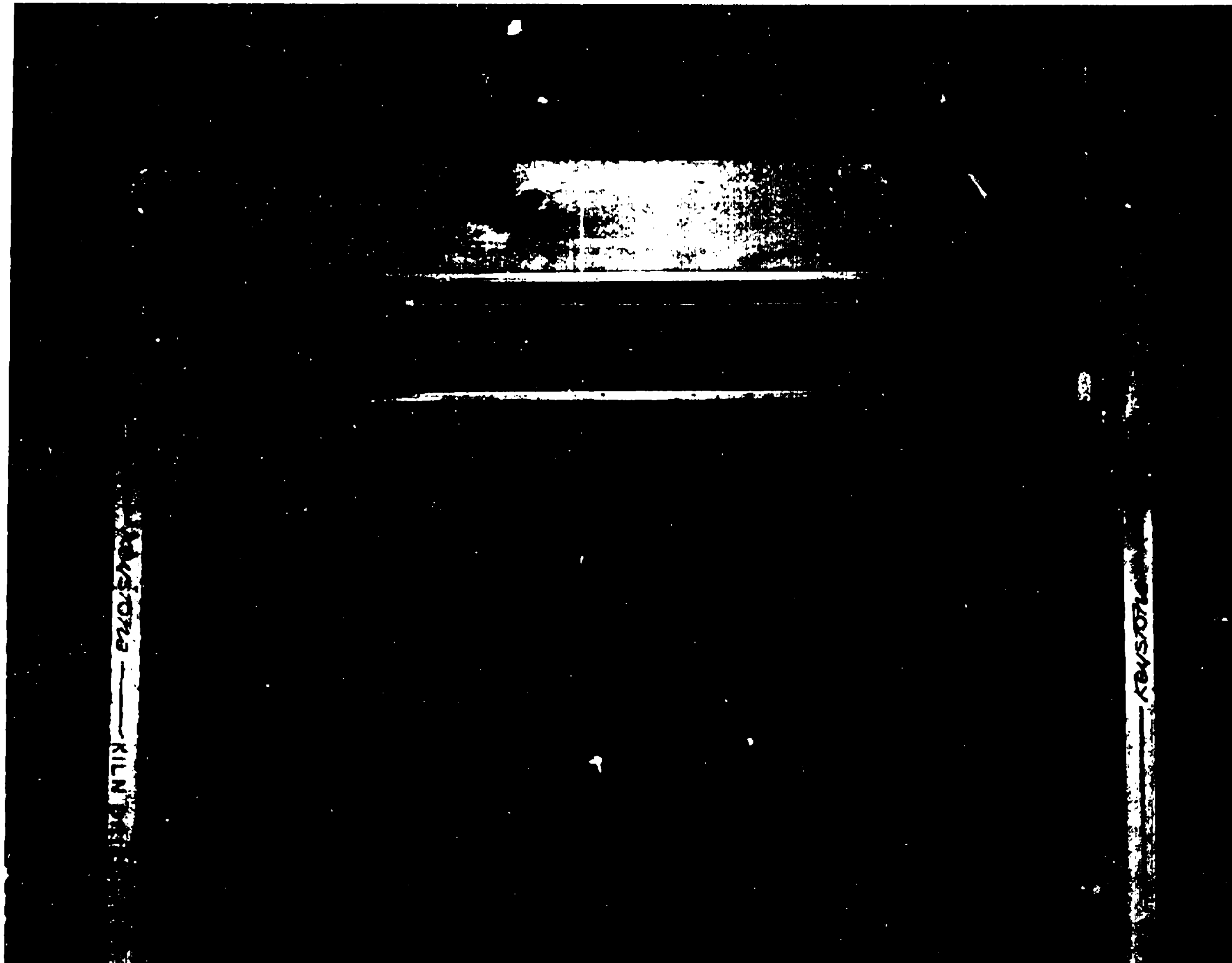

Figure 16. 1956 holder in place for moment of inertia measurement about YZ axis.

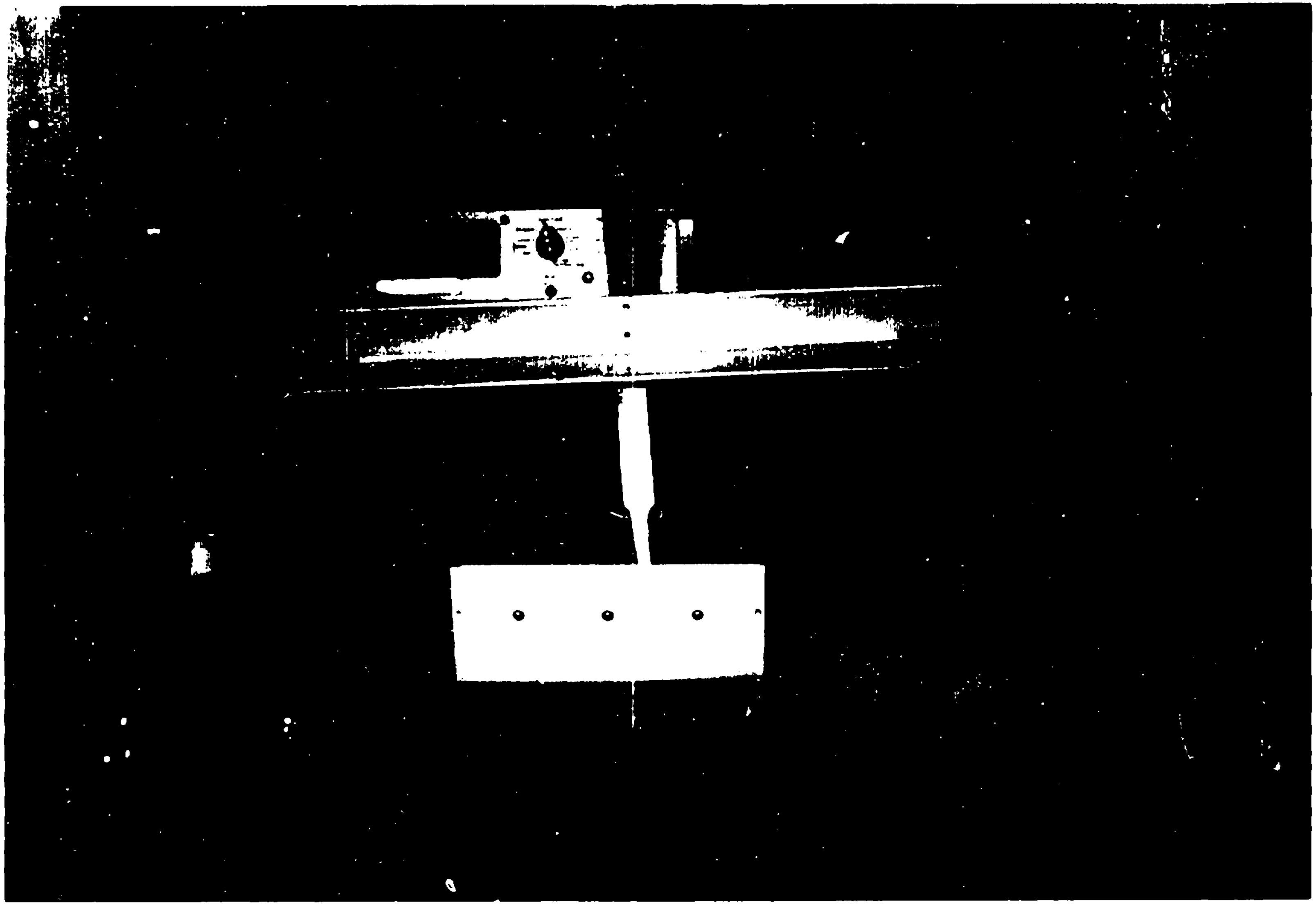

Figure 17. Photocell device for measurement of periods of oscillation.

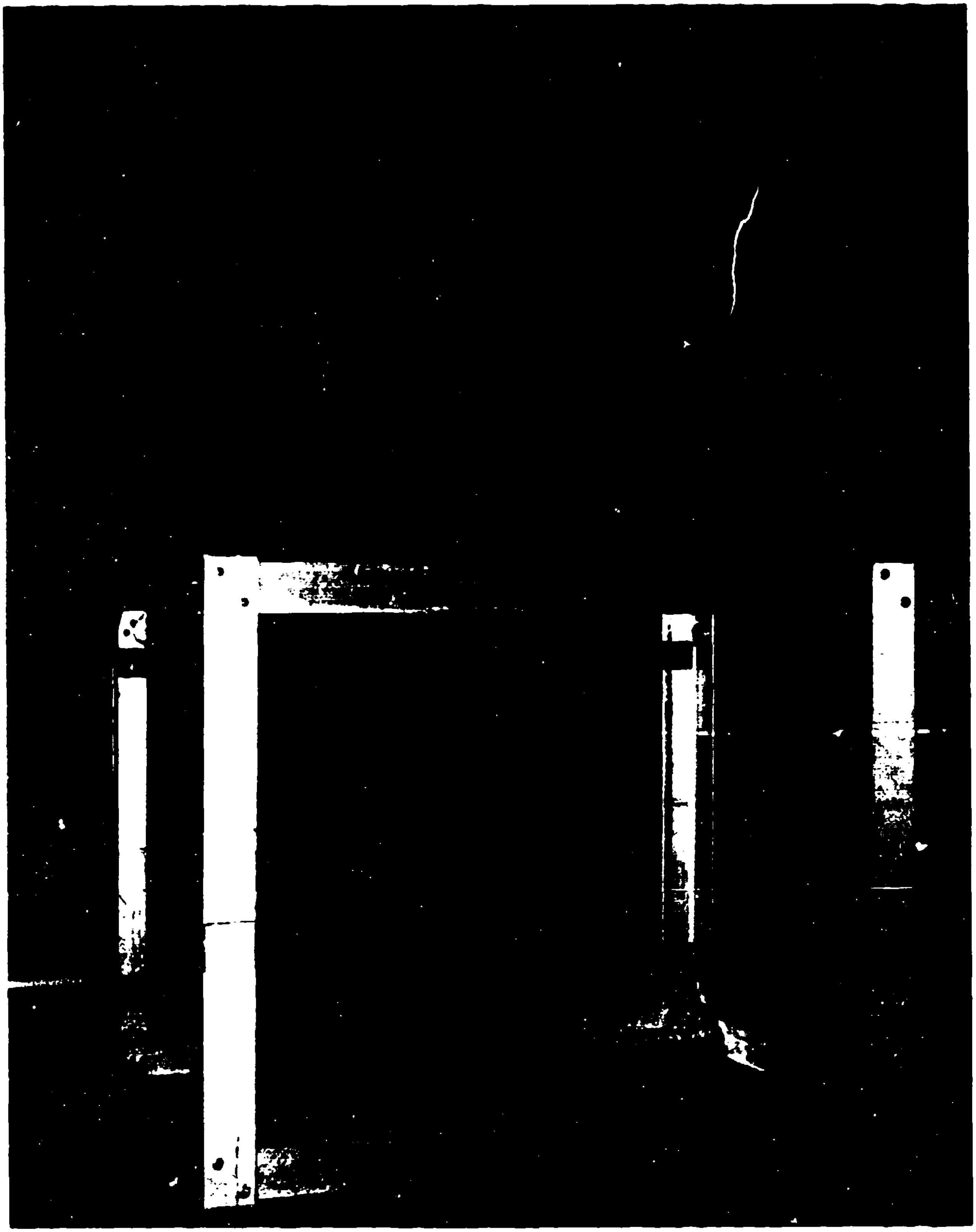

Figure 18. Modified holder and steel I-beam used to validate experimental data.

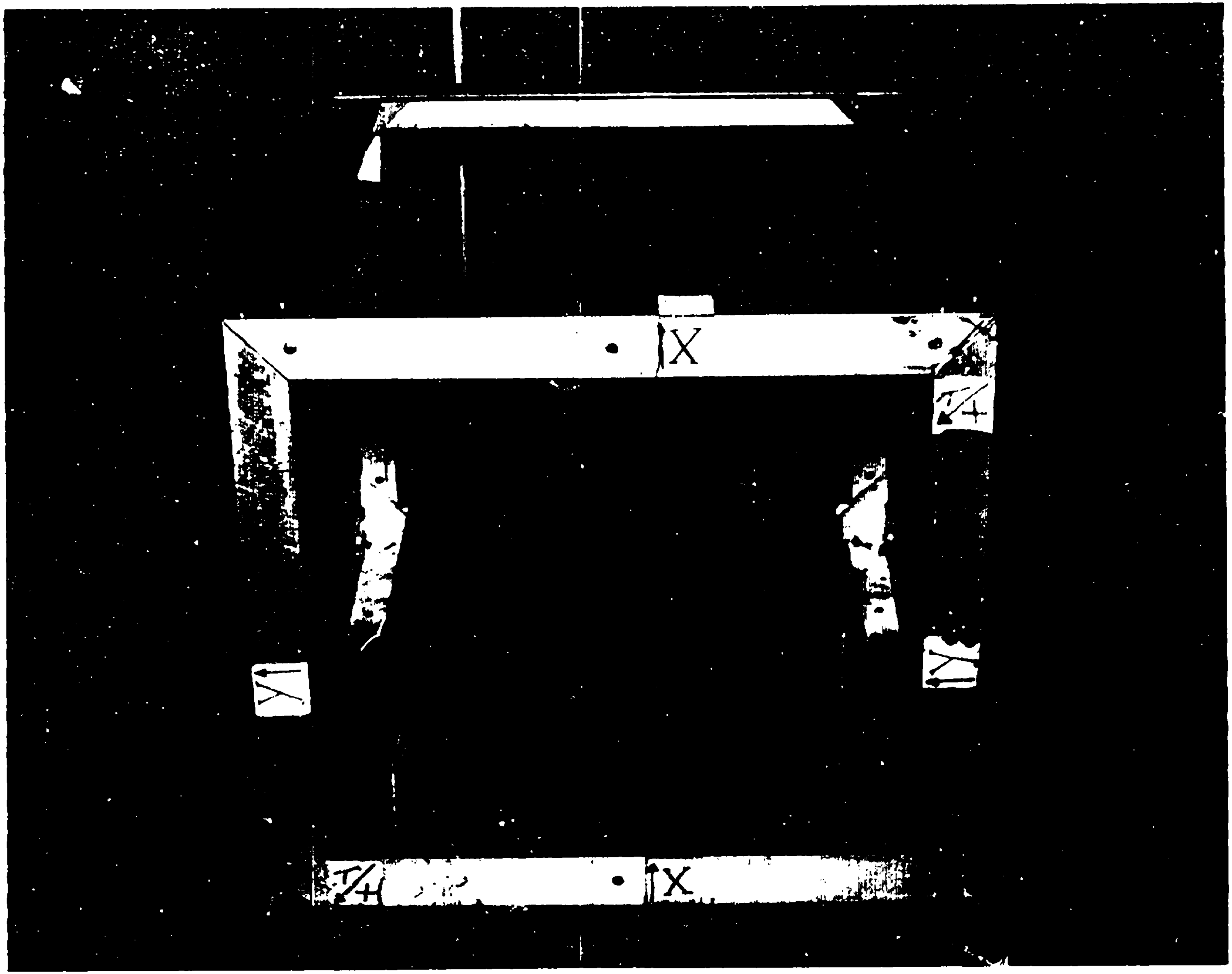

Figure 19. I-beam mounted in holder.

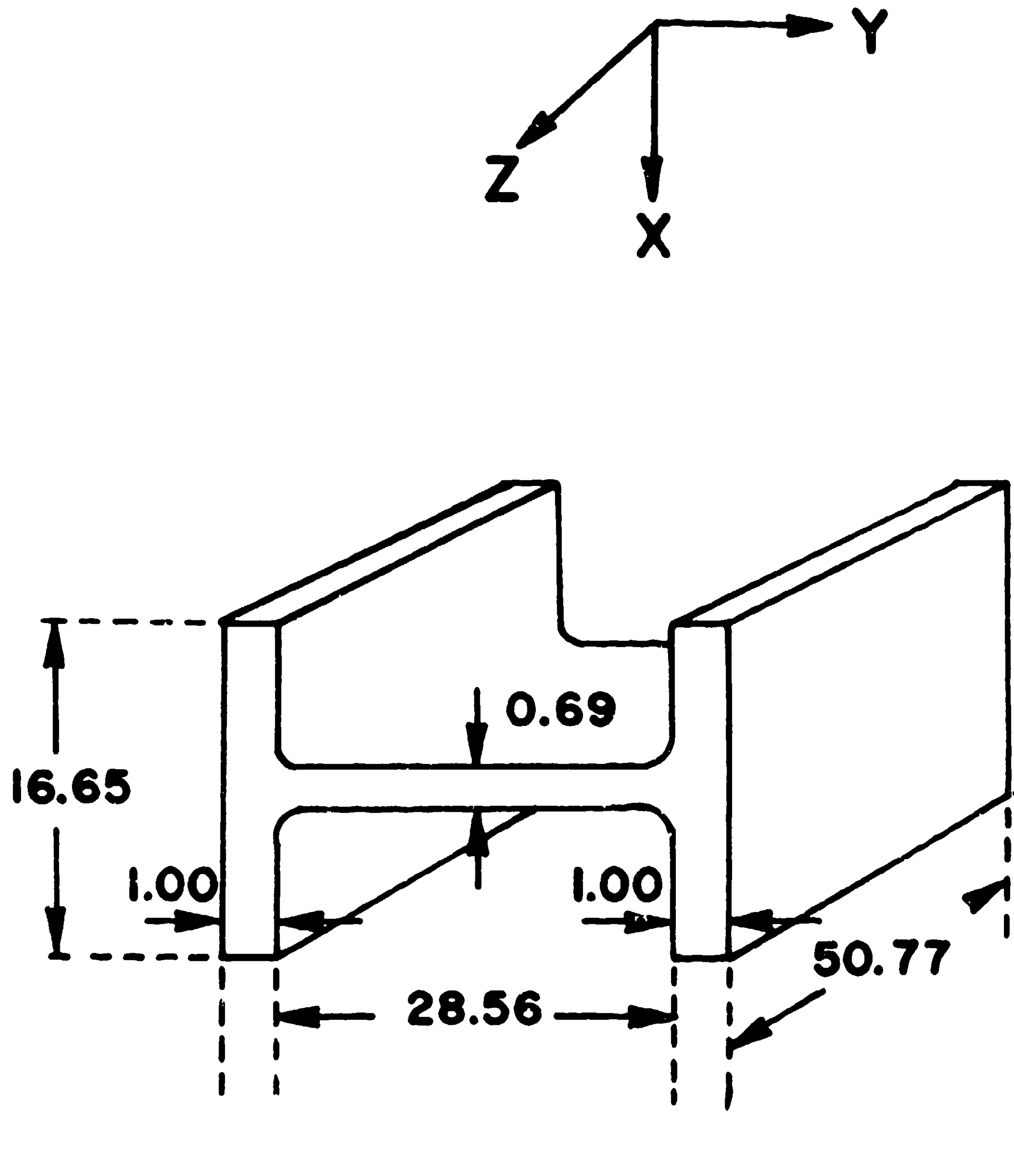

Figure 20. Schematic drawing of I-beam showing dimensions in centimeters.

Table 3

Deviation of Measured Inertia Tensor from Theoretical Values

	Inertia Tensor ($kg \cdot m^2$)					
	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
Measured Value	.8333	.5262	.3974	-.0002	-.1016	.0192
Deviation from Theoretical Value	+.0370 (+4.6%)	+.0425 (+8.8%)	+.0235 (+6.3%)	-.0002 -	-.1016 -	+.0192 -

These results indicate that the system measures moments of inertia with a reasonable degree of accuracy. The products of inertia, with the exception of I_{xz}, were reasonably close to zero. The product I_{xz}, however, appears to have been calculated with a lesser degree of accuracy.

The products of inertia should be expected to be the least accurate of all the inertial values because they involve the greatest number of steps of computation. Any errors made in the initial measurement of mass, CM, and periods of oscillation are amplified with each computation. For a given accuracy of .01 kg for mass, .002 m for effective pendulum length, and .0002 sec for period of oscillation, the maximum error in a computed moment of inertia would be approximately .06 $kg \cdot m^2$. Since three moments of inertia are used to calculate each product of inertia (see Equations 9, 10, and 11) and, given an accuracy of .05 degrees in measuring the orientation angle of the diagonal axis, the maximum error in a given product of inertia is approximately .14 $kg \cdot m^2$. It must be emphasized that these errors are for the worst possible case. The actual errors are probably less than this. It is conceivable, however, that the -.1016 $kg \cdot m^2$ for the I_{xz} product of inertia of the I-beam could have arisen from the magnification of individual errors in the measuring process.

Results

The results of the inertial measurements of the ALICE, 1956, and Commercial backpacks are listed in Tables 4, 5, and 6, respectively. The tables list the mass, the three components of CM, and the moments and products of inertia for each of the six loading conditions.

Mass

The ALICE was the heaviest of the packs, averaging approximately .6 kg more than the 1956 pack. The Commercial pack was the lightest of the three, averaging approximately .25 kg less than the 1956.

The attached weights added approximately 9 kg to the masses of the backpacks above those of the basic load. There were some fluctuations in the masses of each pack. These were due to slight variations between loading conditions in the masses of the added weights and the amounts of tape and shoelaces needed to attach the weights. Because of its relatively loose attachments to the frame, the Commercial pack had to be secured with tape wrapped around the body of the pack for added rigidity.

Center of Mass

The CM results are reported relative to the origin at the geometric center of each holder. Since the origin is the same for each loading configuration within a given pack, any change in the CM location from changing the load can easily be seen.

The results show that positioning the load in the pack either low or high can produce moderate to large changes in the Z component of the CM. Compared to the basic load low condition (L.C. 1), loading the equipment high (L.C. 2) raised the CM by 4.2 cm in the ALICE pack, 3.6 cm in the 1956, and 7.0 cm in the Commercial.

The addition of weights to either the bottom (L.C. 3) or the top of the packs (L.C. 4) produced very substantial changes in the Z component of the CM. Moving the weights from the bottom to the top of the packs raised the CM by 17.9 cm in the ALICE pack 16.2 cm in the 1956, and 21.9 cm in the Commercial.

Changing the weights from the sides (L.C. 5) to the front of the packs (L.C. 6) moved the X component of the CM further away from the pack frame by 6.0 cm in both the ALICE and 1956 backpacks, but only 4.9 cm in the Commercial. These results, like those mentioned above, are consistent with the design differences between the Commercial pack and the Army packs. The Commercial pack is taller, somewhat wider, and less deep than the Army packs.

Table 4

Inertial Properties of ALICE Backpack

Loading Configuration	Mass (kg)	Center of Mass (m)			Inertia Tensor ($kg \cdot m^2$)					
		x	y	z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
1. Basic load - low	15.07	.028	.003	-.028	.57	.53	.37	-.01	-.03	.03
2. Basic load - high	15.08	.016	-.008	.014	.63	.60	.39	-.01	.00	.03
3. Weights - bottom	23.97	.014	.009	-.080	.92	.86	.46	-.02	-.02	.05
4. Weights - top	23.99	.001	.005	.099	.83	.77	.43	-.03	-.05	-.02
5. Weights - sides	24.04	.018	.008	.007	.96	.50	.83	-.01	-.15*	.04
6. Weights - front	24.07	.078	.002	.010	.68	.80	.62	-.04	.01	.07

* This value appears to be erroneous, but it is reported for the completeness of the data.

Table 5

Inertial Properties of 1956 Backpack

Loading Configuration	Mass (kg)	Center of Mass (m)			Inertia Tensor ($kg \cdot m^2$)					
		x	y	z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
1. Basic load - low	14.50	-.009	.006	.016	.50	.45	.33	-.01	.02	.03
2. Basic load - high	14.49	-.019	.001	.052	.52	.46	.33	-.01	.02	.00
3. Weights - bottom	23.37	.010	.005	-.047	.94	.88	.47	-.01	.01	.20*
4. Weights - top	23.38	-.015	-.002	.115	.73	.66	.49	.00	-.02	.04
5. Weights - sides	23.45	-.018	.006	.053	.91	.46	.81	-.02	-.15*	.07
6. Weights - front	23.48	.042	.007	.044	.63	.70	.59	.01	.04	.07

* These values appear to be erroneous, but they are reported for completeness of the data.

Table 6

Inertial Properties of the Commercial Backpack

Loading Configuration	Mass (kg)	Center of Mass (m)			Inertia Tensor ($kg \cdot m^2$)					
		x	y	z	I_{xx}	I_{yy}	I_{zz}	I_{xy}	I_{xz}	I_{yz}
1. Basic load - low	14.25	-.011	-.004	.008	.78	.68	.30	-.01	-.02	.02
2. Basic load - high	14.27	-.012	-.003	.078	.76	.68	.32	-.01	-.04	.01
3. Weights - bottom	23.17	-.015	-.001	-.089	1.51	1.43	.40	-.01	-.03	.07
4. Weights - top	23.15	-.012	.002	.124	1.30	1.22	.41	-.01	-.05	.02
5. Weights - sides	23.15	-.016	.001	.020	1.22	.78	.77	-.01	-.08	.04
6. Weights - front	23.19	.033	-.004	.040	1.02	1.01	.47	.00	.00	.07

Each pack was placed in its respective holder with its frame centered and firmly mounted against the rear side of the holder. Although it does not exactly duplicate the position of the pack CM relative to the body of the load carrier, it is possible to get a better idea of how far away the CM would be from a person's back if the X component were expressed relative to the rear edge of the holder. Table 7 lists these values for each backpack.

Table 7

X Component of CM Expressed Relative to the Rear Edge of Holder

Loading Configuration	ALICE	1956 (meters)	Commercial
1. Basic load - low	.231	.195	.154
2. Basic load - high	.220	.185	.153
3. Weights - bottom	.218	.214	.150
4. Weights - top	.205	.189	.153
5. Weights - sides	.222	.186	.149
6. Weights - front	.282	.246	.198
(Average)	(.230)	(.202)	(.159)

The results show that the CM of the Commercial pack consistently fell closer to the rear edge of the holder than that of either of the Army packs (on the average, 4.3 cm closer than the 1956, 7.1 cm closer than the ALICE). This result was expected. The depth of the Commercial pack is much less than either of the Army packs. What was not expected is that the CM of the 1956 pack was, on the average, 2.8 cm closer to the edge of the holder than that of the ALICE. This was probably due to the extension of the ALICE pack frame where it comes in contact with the lower back. This places the entire pack further away from the body.

The Y coordinate of the CM was within one cm of zero in all cases. This means that the packs were loaded approximately symmetrically and that the CM always fell very close to the midline.

Expressing the Z component of each pack CM relative to a point on the pack frame at the level of the shoulder strap attachments would allow a comparison between packs. These values are listed in Table 8.

Table 8

Z Component of the CM Expressed Relative to
Each Backpack Frame where the Shoulder Straps Attach

Loading Configuration	ALICE	1956 (meters)	Commercial
1. Basic load - low	-.246	-.253	-.088
2. Basic load - high	-.204	-.217	-.018
3. Weights - bottom	-.298	-.316	-.185
4. Weights - top	-.119	-.154	+.028
5. Weights - sides	-.211	-.216	-.076
6. Weights - front	-.208	-.225	-.056
(Average)	(-.214)	(-.230)	(-.065)

The results shown in Table 8 indicate that the 1956 backpack consistently had the lowest CM of the three. The ALICE backpack, however, was nearly as low, averaging just 1.6 cm more than the 1956. The Commercial pack consistently had a higher CM than either of the Army packs (14.9 cm higher than the ALICE, 16.5 cm higher than the 1956). This was, once again, expected. The design of the Commercial pack places the entire pack higher relative to the shoulder straps than either of the Army packs.

Inertia Tensor

With the exception of the three cases noted in Tables 4 and 5, all of the products of inertia were relatively small. Because of this and the possibility of rather large errors in the product terms, the X, Y, and Z coordinate axes were considered to approximate principal axes of inertia.

The overall results for each backpack show that the two Army packs had very similar moments of inertia for each loading configuration. The moments of inertia for the 1956 pack were, on the average, a bit smaller than those of the ALICE. This was probably due to the lighter 1956 frame. The Commercial pack had the lowest values for I_{xx}, but had substantially higher values than the Army packs for both I_{xx} and I_{yy}. Once again this is consistent with the design differences between the Commercial and the Army packs.

The results show little differences in moments of inertia between positioning the basic load low or high (L.C. 1 and L.C. 2). This occurred in spite of the changes in CM location between the two conditions.

The addition of weights generally increased all moments of inertia from their respective basic load values. Adding weights to the bottom (L.C. 3) or top (L.C. 4) produced relatively large increases in I_{xx} and I_{yy}, but less of an increase in I_{zz}. This was expected for L.C. 3 and L.C. 4 because the weights were placed very close to the Z axis, but farther away from both the X and Y axes. What was somewhat of a surprise, however, was that placing the weights on top generally produced smaller moments of inertia than placing the weights on the bottom.

Placing the weights on the sides (L.C. 5) produced a relatively large increase in I_{xx}, the largest increase in I_{zz}, but did not substantially increase I_{yy}. In this configuration the weights were furthest from the vertical Z axis but very close to the Y axis running side to side. The addition of weights on the sides, however, should not <u>decrease</u> the value of I_{yy} as was apparently the case for the ALICE pack. Although there were some differences in the CM location between L.C. 1, L.C. 2, and L.C. 5 for the ALICE pack, which might account for the differences in I_{yy}, this reported decrease is probably an error.

Finally, placing the weights on the front of the packs (L.C. 6) produced the smallest increase in I_{xx} since the weights were placed rather close to the X axis. I_{yy} and I_{zz} were each increased substantially. I_{zz} was not, however, increased nearly as much as when the weights were placed on the sides.

Discussion

A loaded backpack is not a delicate piece of machinery that is balanced precisely so that it can spin about an axis in a stable manner. In fact, the exact orientation of the backpack during a maneuver probably will vary with each individual who carries it. For these reasons, the reported accuracy of the mass, CM, and inertia tensor of each backpack is probably well within any limits needed in this study.

Before discussing specific results, this section will present certain inertial properties desirable in a backpack, based on mechanical principles. These are discussed below.

(1) Mass. The backpack should be as light as possible. This is important from the standpoint of minimizing the gravitational force that the pack exerts on the body and also of minimizing the inertial forces exerted on the body by the backpack during periods of linear acceleration.

(2) CM X component. The CM of the backpack should fall as close to the body as possible. This minimizes the amount of postural change needed to support the pack in an upright position. This is perhaps one of the most important considerations.

(3) CM Y component. The backpack should be symmetrically designed and loaded from side to side. This is a fairly obvious point. Having the CM of the pack fall in the sagittal plane of the body would also minimize the amount of postural change needed to support the pack.

(4) CM Z component. The CM of the pack should be as low as possible. This contributes to the stability of the carrier-pack system although it also results in greater forward lean of the body than a high CM.

(5) Moments of inertia. The backpack should possess as small a moment of inertia as possible about each of its principal axes, especially Y and Z. I_{xx} may not be as important as I_{yy} and I_{zz} because there are relatively few movements in a load carrying situation which involve rotation about the X (dorsoventral) axis. (It is assumed that a person carrying a backpack would not regularly perform cartwheels!) Rotation about the Y (transverse) axis would occur in a "hitting-the-dirt" maneuver. Rotation about the Z (longitudinal) axis would occur during a change in direction while moving upright. A small moment of inertia about a particular axis of rotation would minimize the inertial torques and their resulting forces exerted on the body by the backpack during periods of angular acceleration.

There are a number of considerations modifying these desirable characteristics of a backpack. What is desirable may not always be feasible and vice versa. For example, it was shown in the results that loading the equipment "high" or "low" can make a substantial change in the Z component of the pack CM. One must, however, be able to access necessary items easily, and thus a person would probably place those items on top. The Commercial pack has an advantage in this respect over the Army packs because it has two main

compartments. Thus a heavy item could be loaded in the lower compartment and still be removed easily without disturbing the contents in the upper compartment. A major drawback of the pack used with the ALICE and the 1956 systems is that it has only a single main compartment.

Other advantages of the Commercial backpack are that it is lighter and places the CM closer to the body than either of the Army backpacks. It also, however, has a CM that is substantially higher than the ALICE or the 1956. This is, in the opinion of the authors, a disadvantage of this particular Commercial design.

In addition, the Commercial backpack has substantially higher values for I_{xx} and I_{yy} than either of the Army backpacks. Although this may also be considered a disadvantage, the limitations of reporting only local moments of inertia about each backpack's CM, rather than the moments of inertia of the total carrier-backpack system, must be recognized. If its CM is closer to the total system CM, a backpack with higher local moments of inertia may actually contribute less to the moments of inertia of the total system than another backpack with lower local moments of inertia. Extension of this work to the total system would shed light on this and other backpack-carrier interactions.

Recognizing that inertial properties of the backpacks were examined here, rather than the properties of the total carrier-backpack system, some general recommendations for pack loading can be made on the basis of the results of this study. The most desirable combinations of the loading configurations tested are a low placement of the basic load within the pack and the strapping of any extra items to the sides and/or the bottom of the pack. It was found that placing the two, 4.56-kg weights on the sides of the pack produced a low value for I_{yy}, but not for I_{zz}. Placing the weights on the bottom of the pack produced a low value for I_{zz} but not for I_{yy}. In either case, extra items should be placed as close to the pack frame as possible in order to keep the CM as close to the body as possible. Thus, one should avoid placing items on the front of the pack. It should be noted that small pouches are positioned on the front of the Army pack used in this study. If anything other than very light items are to be placed in these pouches, a preferable design would be to locate the pouches on the bottom or the sides of the pack.

Placing added loads on the top of the pack should be avoided; it creates an unstable system by raising the CM. However, the location of the CM along the Z axis affects the amount of postural change needed to support the load, as well as the stability of the system. All else being equal, in order to place the CM of the pack over the feet, a person would lean forward more when carrying a backpack with a low CM than one with a high CM. Thus, a high CM has the advantage of requiring less postural change, but the disadvantage of making the entire system less stable. The relative importance of system stability and of postural change may depend to a large extent on the activity to be performed.

As mentioned previously, the assessment of the inertial properties of the human load carrier plus the backpack is a logical extension of this research. By combining the information obtained in this study with research findings related to the inertial properties of the human body, a mathematical model of this total system has been developed[4,5]. The model, which can be exercised by use of a Fortran program, allows mathematical determinations to be made of the best locations for added pack loads without the necessity for repeated experimental analyses of inertial properties.

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[4]Hanavan, E.P. "A Mathematical Model of the Human Body" (Tech. Rep. AMRL-TR 64-102). Wright-Patterson Air Force Base, Ohio: Aerospace Medical Research Laboratory, 1964. (AD-608-463)

[5]Martin, P.E., R.N. Hinrichs, I. Shin, and R.C. Nelson. "Volume IV. A Mathematical Model of the Inertial Properties of a Carrier-Backpack System" (Tech. Rep. NATICK/TR-82/022). Natick, Massachusetts: US Army Natick Research and Development Laboratories, May 1982.

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5. Martin, P.E., R.N. Hinrichs, I. Shin, and R.C. Nelson. "Volume IV. A Mathematical Model of the Inertial Properties of a Carrier-Backpack System" (Tech. Rep. NATICK/TR/82/022). Natick, Massachusetts: US Army Natick Research and Development Laboratories, May 1982.

Appendix A

Clothing and Equipment Used in This Study

Clothing and Sleeping Gear

The items stowed in the packs are standard products from the Army's inventory. The Army nomenclature for each item and its military specification, which contains a description of the item, are listed below.

Nomenclature	Specification
Mattress, Pneumatic, Insulated	MIL-M-43968
Overshoes, Rubber, 5-Buckle	MIL-O-836E
Poncho, Wet Weather	MIL-P-43700
Bag, Waterproof, Clothing	MIL-B-3108
Sleeping Bag, Intermediate Cold, Synthetic Fill	MIL-S-44016
Coat, Cotton/Nylon, Wind Resistant (field)	MIL-C-43455
Liner Coat, Nylon Quilted (field)	MIL-L-43536
Trousers, Cotton/Nylon, Wind Resistant (field)	MIL-T-43497
Liner Trousers, Nylon Quilted (field)	MIL-L-43498
Undershirt, Cotton/Wool	MIL-U-43262
Drawers, Cotton/Wool	MIL-D-43261
Socks, Wool, Cushion Sole	MIL-S-48
Handkerchief	DDD-H-71H
Washcloth, Terry, Cotton	DDD-W-80D

Backpacks

Three pack and frame combinations were used in this study. They were all external-frame systems. The same pack, the ALICE, was used on two of the frames, the ALICE frame and the 1956 frame. The packs and frames are described below.

ALICE Pack (Figure A-1). This standard Army equipment is a component of a load carrying system designated as All-Purpose Lightweight Individual Carrying Equipment (ALICE). The ALICE pack is made of nylon duck and nylon webbing and weighs 1.3 kg. It has a large, top-loading, main compartment, an outside pocket on each of two sides and the front, and three smaller pockets above the center outside pocket. The maximum capacity of the pack is approximately 32 kg. The main compartment can be closed by means of a drawstring and is covered by a storm flap. The flap is secured by two vertical straps which encircle the pack. Each outside pocket has a drawstring closure and is covered by a flap which is secured by a single strap. Strips of webbing sewn on the outside surface of the main compartment can be used for attaching items. A pocket large enough to accommodate a field radio is sewn inside the main compartment on the surface closest to the wearer's back. There are also "D" rings and tie strings inside the main compartment which can be used to shorten the pack if it is not filled to capacity. The pack is attached to a frame by means of an envelope at the top of the pack which slides over the top of the frame and a strap with a buckle on the bottom of each side of the pack which wraps around the frame.

ALICE Frame (Figure A-2). This frame with its associated straps was developed by the Army in the early 1970's for use with the ALICE pack. It was recently replaced as standard Army equipment by another frame/strap system. However, a supply of the ALICE frame remains in the Army's inventory and the frame remains in use by Army personnel.

Figure A-1. ALICE pack.

Figure A-1. ALICE pack.

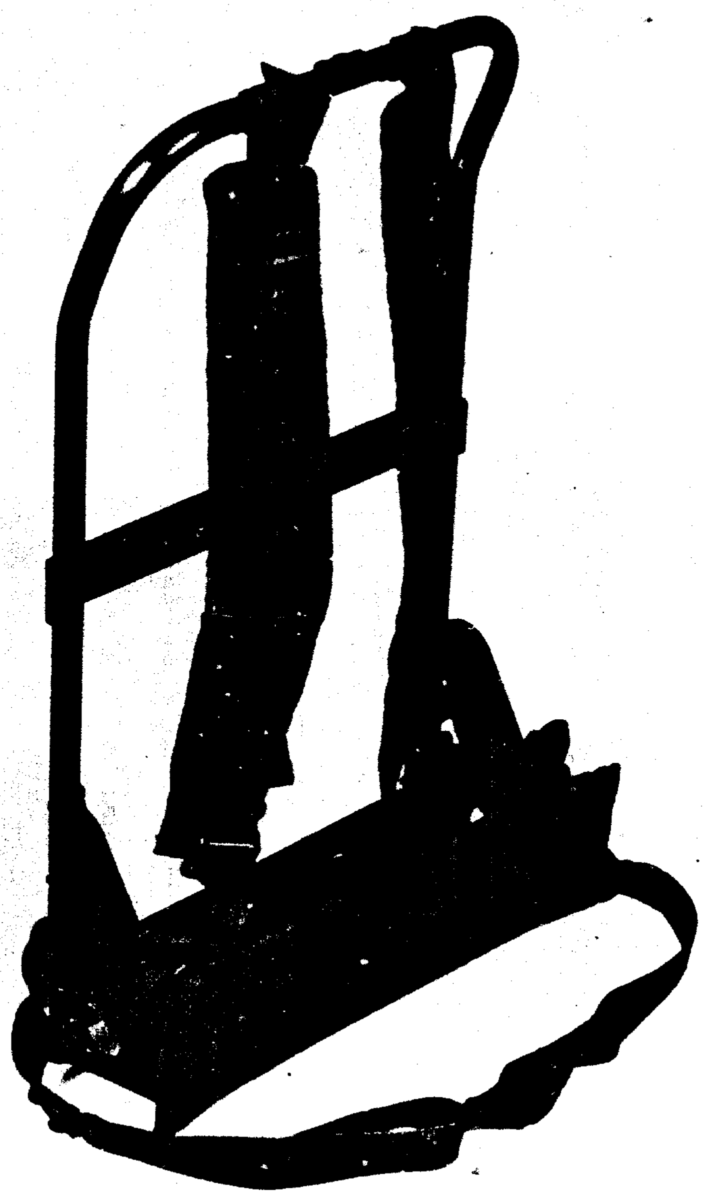

Figure A-2. ALICE frame.

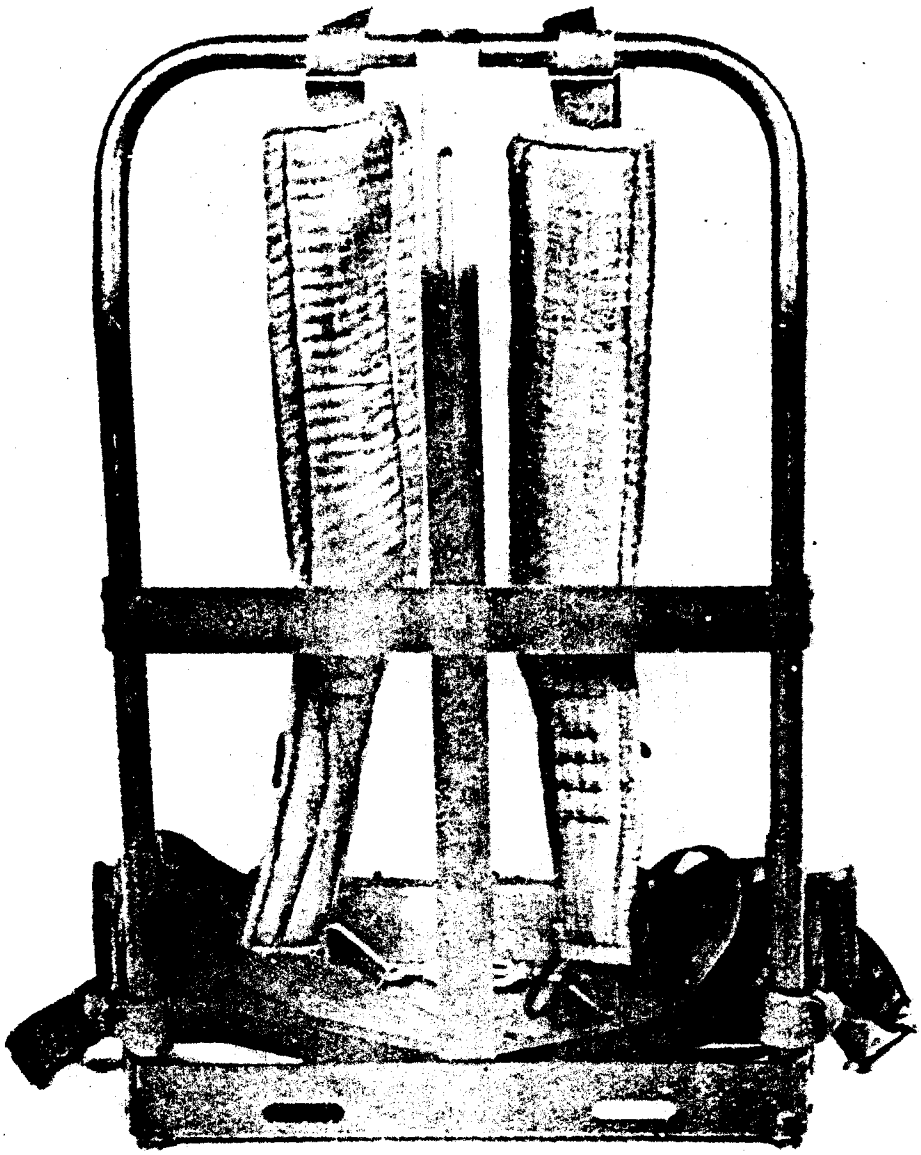

Figure A-2. ALICE frame.

Figure A-2. ALICE frame.

This frame is structured of aluminum tubing. It is 50.8 cm high and 31.1 cm wide. There are two, aluminum horizontal members made from flat stock which extend from one side of the frame to the other and are riveted to the aluminum tubing. One, aluminum, vertical member, also made from flat stock, is riveted to the top and the bottom of the frame. Toward the top of the frame, this vertical piece and the aluminum tubing are angled toward the wearer's back. Two metal loops are attached to the top, horizontal, tubular portion of the frame. These are used to retain one end of the shoulder straps. There is also a grommet at the lower portion of each side of the frame through which the other end of each shoulder strap passes and is secured.

The top portion of each shoulder strap, measuring 38.7 cm long and 6.4 cm wide, is made of a cloth spacer material covered with nylon duck and nylon webbing. The remainder of the strap is narrow nylon webbing. A quick-release device is incorporated into the left shoulder strap and both straps have buckles for length adjustments. The lower back strap, which is 34.3 cm long and 7.6 cm high, is also made of a cloth spacer material covered with nylon duck. The back strap is secured to the frame by use of webbing which is attached to a turnbuckle. The waist belt is made of two pieces of nylon webbing 2.5 cm wide. One end of each piece is wrapped around the lower, tubular portion of the frame. Each piece includes a buckle for adjusting the length of the belt. The belt is secured around the waist by a metal and plastic quick-release device. The frame with its associated straps weighs 1.4 kg.

<u>1956 Frame</u> (Figure A-3). This frame, the predecessor of the ALICE, is no longer in use by Army personnel. It was included in this study, because unlike the ALICE, the 1956 has a "wrap-around" design. This frame is constructed of aluminum tubing. It is 53.3 cm high, 33.0 cm wide at the top, and 43.2 cm wide at the bottom. A top, horizontal bar and two vertical bars are formed from one continuous length of tubing. Two other pieces of aluminum tubing extend from one side of the frame to the other, joining the vertical bars at the bottom of the frame and at a point approximately 32 cm from the top of the frame. The bottom of each side of the 1956 is formed of a piece of D-shaped tubing. Metal loops are riveted to various parts of the frame; these are used to keep straps and webbing in place. The upper portions of the two vertical bars are angled toward the wearer's back and each of the three horizontal bars is curved such that the frame is concave relative to the wearer's back.

Although the 1956 was not designed to be used with the ALICE pack, the frame can accommodate this pack and they were used together in this study. The pack was secured to the frame by passing the two vertical straps which encircle the pack through two of the four metal loops at the top of the frame and by wrapping the strap at the bottom of each side of the pack around the D-shaped section of the frame. The shoulder and waist straps from the ALICE frame were also used on the 1956. One end of each shoulder strap was secured to the top of the frame by use of two of the metal loops. The lower portion of each shoulder strap was wrapped around a D-section, as was one end of each piece of the waist belt. The lower back strap used

Figure A-3 1956 frame.

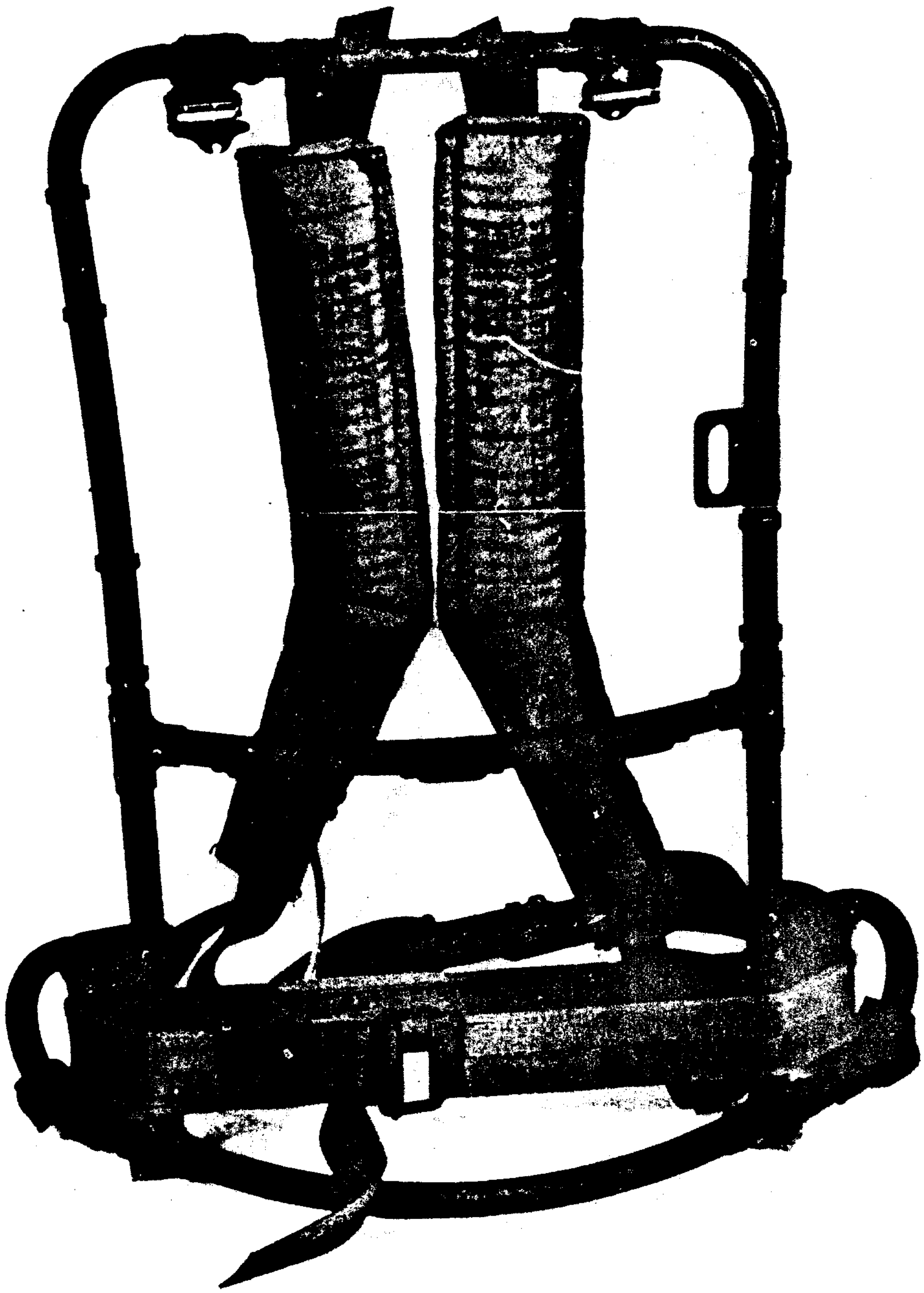

Figure A-3. 1956 frame.

Figure A-3. 1956 frame.

was the one which is supplied with the 1956 frame. It is comprised of a piece of nylon webbing, 4.2 cm high, and a buckle. The back strap encircles the frame, running through the D-shaped sections. The portion of the strap closest to the wearer's back is 37.5 cm long. The frame with its associated straps weighs 1.2 kg.

Commercial Backpack (Figure A-4). The Camp Trails Astral Model was selected as representative of the frame-pack systems commonly used by hikers and backpackers. The aluminum tubing frame contains two main vertical components 2.5 cm in diameter and 71.5 cm long. The three horizontal tubes are 2 cm in diameter and 37 cm in length. A U shaped brace is attached to both the upper cross brace and vertical tubes for added strength. Two small tubes, 1 cm in Diameter connect all three horizontal braces.

Two padded shoulder straps attach to the upper horizontal brace and to the outer surface of the base of the two vertical tubes. The padded waist belt is attached firmly to the inner surface of the base of the vertical tubes, and by elastic bands to the middle horizontal tube. A mesh band, 13 cm wide, is attached across the vertical tubes on the inner surface. The nylon pack is divided into two main compartments aligned vertically. The upper section which is loaded from the top comprises about 2/3 of the pack space. The lower section is entered via a horizontal zipper opening. Additional compartments are located two on each side and one on the upper part of the back portion of the pack. The opening to the main compartment is controlled by a drawstring and a large cover extends over the pack and attaches to its lower section.

The nomenclature and military specification for each pack and frame included in this study which is or was in the Army's inventory are listed below.

Nomenclature	Specification
Field Pack, Nylon, Large, All-Purpose Lightweight Individual Carrying Equipment (ALICE)	MIL-F-43832
Frame Pack with Straps, LC-1, All-Purpose Lightweight Individual Carrying Equipment (ALICE)	MIL-S-43834
Riveted Frame, 1956, for Lightweight Rucksack	Discontinued

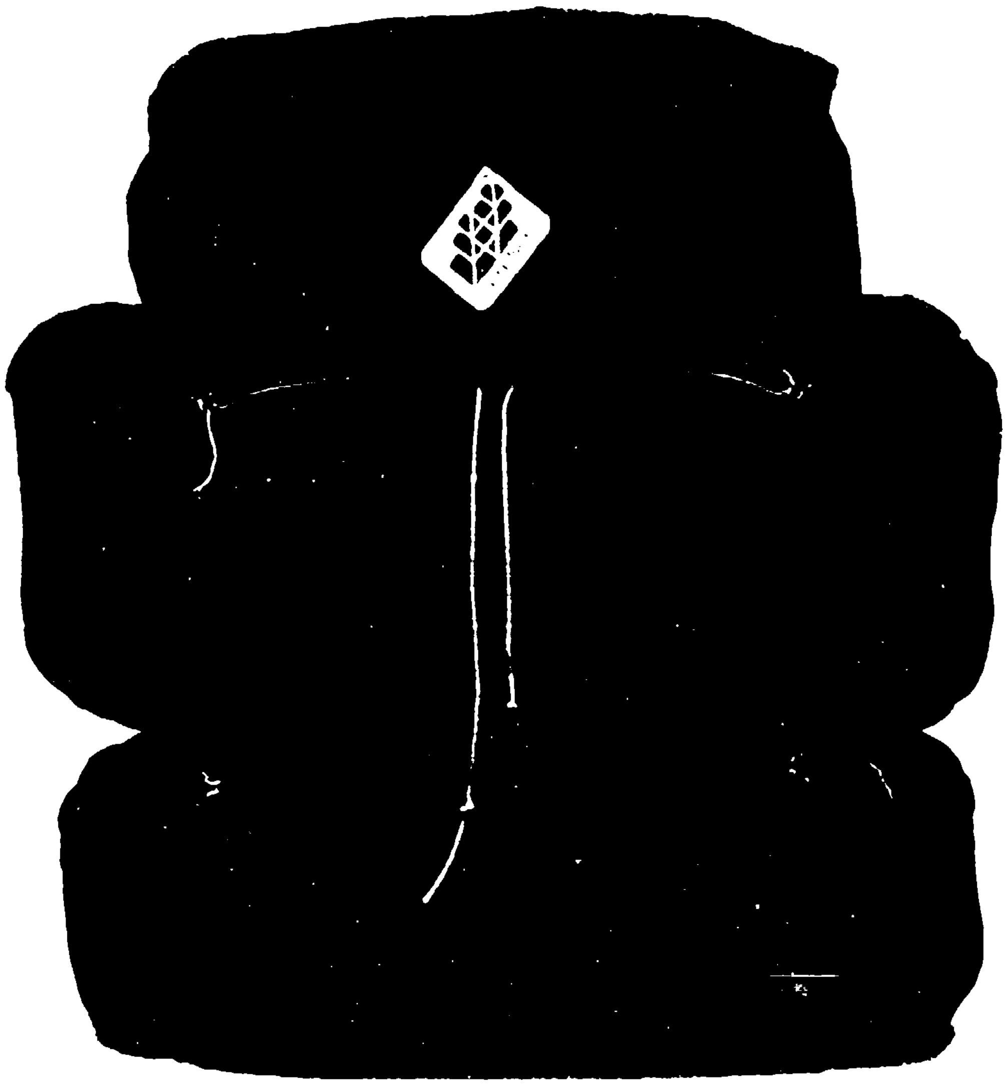

Figure A-4. Commerciai backpack.

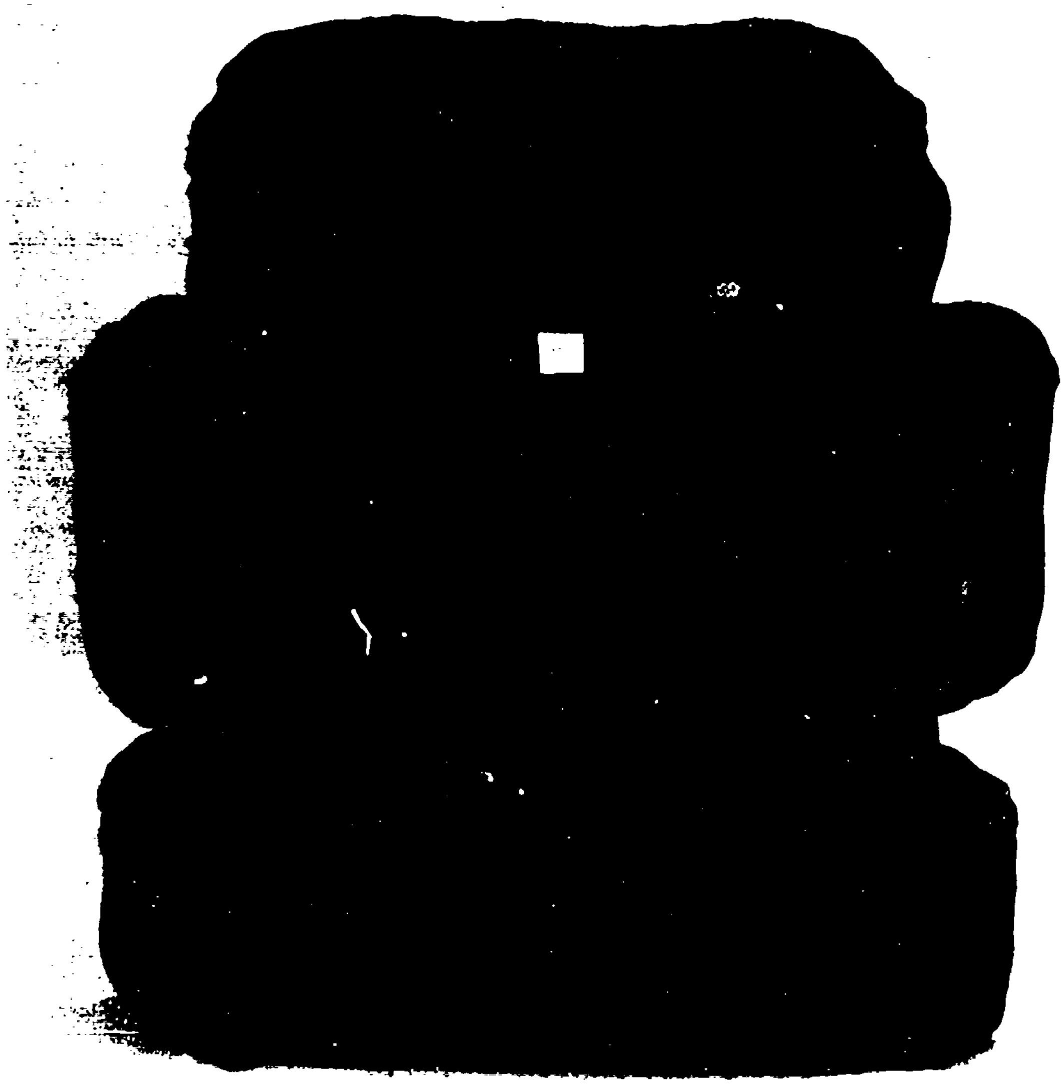

Figure A-4. Commercial backpack.

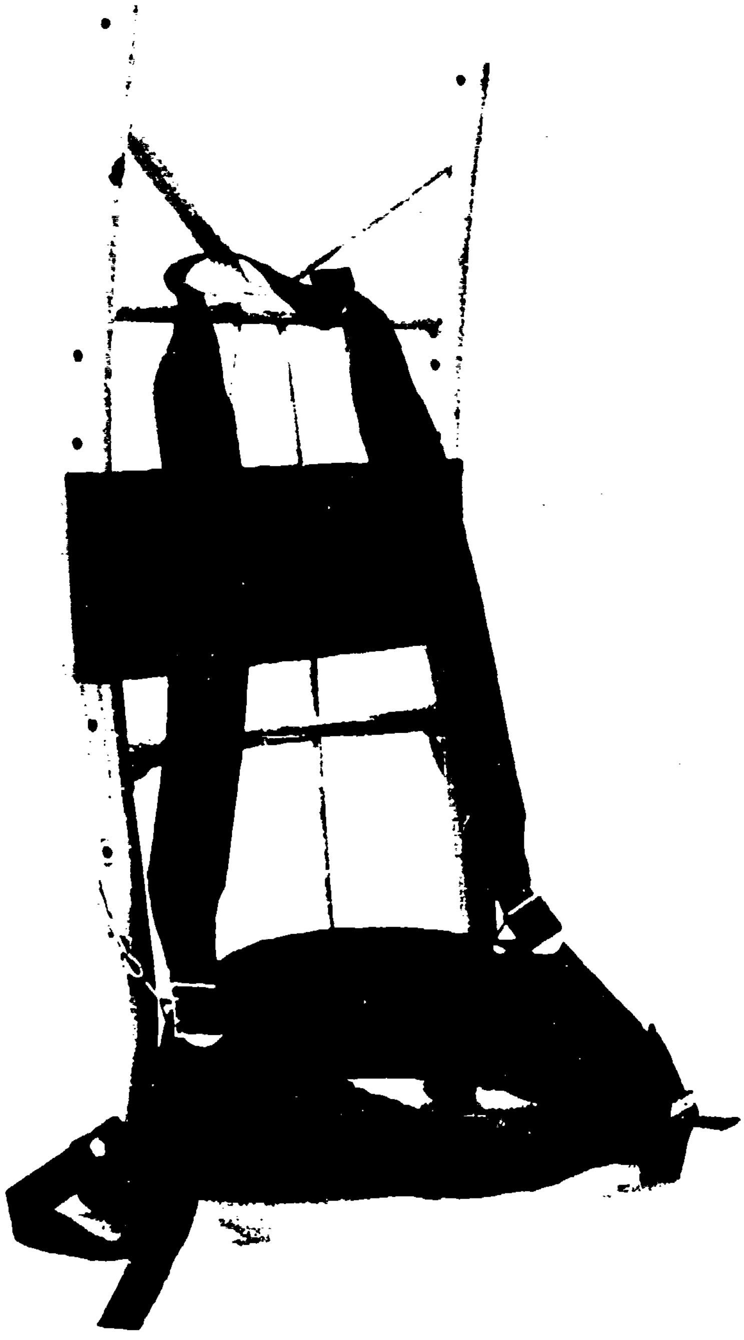

Figure A-4. Commercial backpack.

Figure A-4. Commercial backpack.

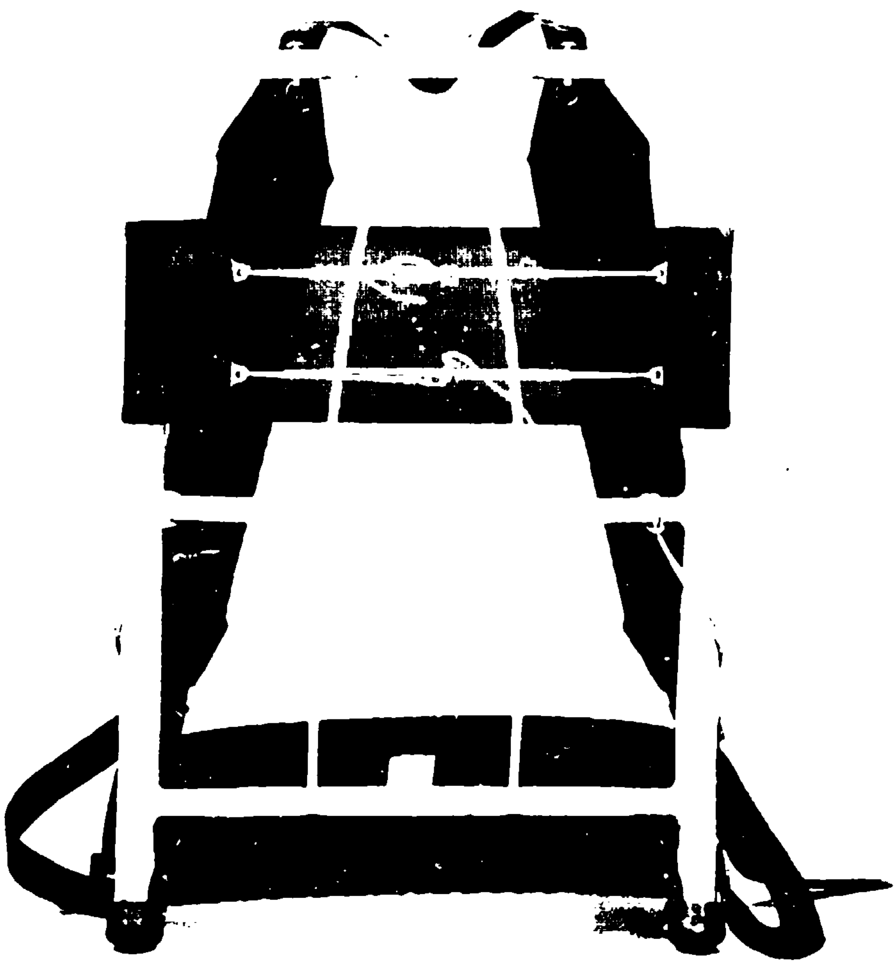

Figure A-4. Commercial backpack.

Appendix B

Computer Program Used to Compute Inertial Properties

```
/*USERID CAM02
// EXEC FWCLC,PARM='NOSOURCE,NOSUBCHK'
//SYSIN DD *
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C         ARMY PROJECT OSCILLATION PROGRAM
C    THIS PROGRAM TAKES MASS, CENTER OF MASS, AND PERIODS OF
C    OSCILLATION OF BOTH THE COMPOSITE SYSTEM (PACK + HOLDER)
C    AND THE HOLDER ALONE AND CALCULATES THE MOMENTS AND PRODUCTS
C    OF INERTIA OF THE PACK ABOUT ITS CENTER OF MASS.
C    PRINCIPAL MOMENTS AND AXES OF INERTIA ARE ALSO COMPUTED.
C
C
C         TERMS ARE DEFINED AS FOLLOWS:
C
C    CONDITIONS--(I)--1=HOLDER, 2=COMPOSITE, 3=SPECIMEN(PACK)
C    AXES--(J)--1=XX, 2=YY, 3=ZZ, 4=XY(DIAG), 5=XZ(DIAG), 6=YZ(DIAG)
C    COMPONENTS--(K)--1=X, 2=Y, 3=Z
C
C         VARIABLES ARE DEFINED AS FOLLOWS:
C
C    ALL MASSES IN KG, COORDINATES AND DISTANCES IN METERS,
C    TIME IN SECONDS, MOMENTS AND PRODUCTS OF INERTIA IN KG*M**2.
C
C    T(I,J)--------PERIODS OF OSCILLATION
C    COHB(J,K)-----COORDINATES OF THE HINGE BAR CM
C    COT(I,J,K)----COORDINATES OF THE CM OF HOLDER(I=1), COMPOSITE(I=2),
C                  AND SPECIMEN(I=3)
C    ANG-----------1. ANGLE BETWEEN X AXIS AND XY DIAGONAL AXIS
C                  2.   "       "    X AXIS AND XZ DIAGONAL AXIS
C                  3.   "       "    Y AXIS AND YZ DIAGONAL AXIS
C    COA(K)--------COORDINATES OF PT A (CENTER OF AXIS OF HINGE BAR)
C    COG(I,K)------COORDINATES OF CM OF HOLDER  /O HINGE BAR(I=1),
C                  AND COMPOSITE W/O HINGE BAR(I=2)
C    D(I,J)--------PARALLEL AXIS DISTANCES
C    AMASS(I)------MASSES  W/O HINGE BAR
C    TMASS(I)------MASSES  W/ HINGE BAR
C    XI(J)---------MOMENTS OF INERTIA OF SPECIMEN ABOUT ITS CM
C    XIP-----------PRODUCTS "    "    "    "    "    "    "
C                  1.  IXY  2.  IXZ  3.  IYZ
C    XIT-----------THE INERTIA TENSOR CONTAINING 1. IXX, 2. IXY,
C                  3. IYY, 4. IXZ, 5. IYZ, 6. IZZ
C    EIGNVL--------PRINCIPAL MOMENTS OF INERTIA
C    EIGNVR--------PRINCIPAL AXES OF INERTIA
C    HHEAD---------HEADER INFO--HOLDER
C    SHEAD---------   "     " --SPECIMEN
C    IHNO----------HOLDER NUMBER
C    ISNO----------SPECIMEN NUMBER
C    LCNO----------LOADING CONDITION NUMBER
C    HBM-----------MASS OF HINGE BAR
C    HBCM----------DISTANCE ABOVE ATTACHMENT SITE TO CM OF HINGE BAR
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
```

```
      DIMENSION T(2,6),COHB(6,3),COT(3,6,3),ANG(3),COA(3),COG(2,3),
     2 D(3,6),AMASS(3),TMASS(2),XI(6),XIP(3)
      DOUBLE PRECISION XIT(6),EIGNVL(3),EIGNVR(3,3),WK(10)
      LOGICAL*1 HHEAD(30),SHEAD(30)
      DATA HBM/1.464/,HBCM/.0953/,COHB/18*0./,IO/3/,IOPT/2/
C
C   READ IN DATA.
C
      READ(5,100)HHEAD,IHNO,AMASS(1),ANG,COA,(COG(1,K),K=1,3),
     2  (T(1,J),J=1,6)
  100 FORMAT(30A1/I1,F9.3,3F10.8/6F10.4/6F10.4)
      DO 999 LL=1,6
      READ(5,150)SHEAD,ISNO,LCNO,AMASS(2),(COG(2,K),K=1,3),
     2  (T(2,J),J=1,6)
  150 FORMAT(30A1/2I1,F8.3,3F10.4/6F10.4)
C
C   CALCULATE TOTAL MASSES AND CM LOCATIONS FOR HOLDER, COMPOSITE,
C   AND SPECIMEN.
C
      DO 200 I=1,2
      TMASS(I)=AMASS(I)+HBM
  200 CONTINUE
C
      WRITE(6,2050)SHEAD,TMASS
 2050 FORMAT(//////1X,T45,30A1///' TMASS'/1X,2F20.3)
C
      COHB(6,1)=COA(1)+HBCM
      IF(IHNO.EQ.4)COHB(6,1)=COA(1)-HBCM
      COHB(3,2)=COA(2)-HBCM
      COHB(5,2)=COA(2)-HBCM
      COHB(1,3)=COA(3)-HBCM
      COHB(2,3)=COHB(1,3)
      COHB(4,3)=COHB(1,3)
C
      WRITE(6,2100)COHB
 2100 FORMAT(///' COHB'/3(6F10.7,/))
C
      DO 300 I=1,2
      DO 250 J=1,6
      DO 225 K=1,3
  225 COT(I,J,K)=(COHB(J,K)*HBM+COG(I,K)*AMASS(I))/TMASS(I)
  250 CONTINUE
  300 CONTINUE
C
      AMASS(3)=AMASS(2)-AMASS(1)
      DO 400 J=1,6
      DO 350 K=1,3
  350 COT(3,J,K)=(TMASS(2)*COT(2,J,K)-TMASS(1)*COT(1,J,K))/AMASS(3)
  400 CONTINUE
C
      WRITE(6,4100)AMASS,COT
 4100 FORMAT(///' AMASS'/3F20.3///' COT'/18(3F20.7/))
```

```
C
C   CALCULATE PARALLEL AXIS DISTANCES TO CM OF HOLDER, COMPOSITE,
C   AND SPECIMEN.
C
      DO 450 I=1,3
      D(I,1)=SQRT(COT(I,1,2)**2+(COT(I,1,3)-COA(3))**2)
      D(I,2)=SQRT(COT(I,2,1)**2+(COT(I,2,3)-COA(3))**2)
      D(I,3)=SQRT(COT(I,3,1)**2+(COT(I,3,2)-COA(2))**2)
      D(I,4)=SQRT((COT(I,4,1)*SIN(ANG(1))+COT(I,4,2)*COS(ANG(1)))**2
     2  +(COT(I,4,3)-COA(3))**2)
      D(I,5)=SQRT((COT(I,5,2)-COA(2))**2+(COT(I,5,1)*SIN(ANG(2))
     2  +COT(I,5,3)*COS(ANG(2)))**2)
      D(I,6)=SQRT((COT(I,6,1)-COA(1))**2+(COT(I,6,3)*COS(ANG(3))
     2  +COT(I,6,2)*SIN(ANG(3)))**2)
  450 CONTINUE
C
      WRITE(6,4600)D
 4600 FORMAT(///' D'/6(3F20.7/))
C
C   CALCULATE 6 MOMENTS OF INERTIA.
C
      DO 500 J=1,6
      CALL MOMIN(TMASS(2),D(2,J),T(2,J),T(1,J),TMASS(1),D(1,J),D(3,J),
     2  XI(J))
  500 CONTINUE
C
C   CALCULATE PRODUCTS OF INERTIA.
C
      CALL PROIN(XI(1),XI(2),XI(4),ANG(1),XIP(1))
      CALL PROIN(XI(2),XI(3),XI(5),ANG(2),XIP(2))
      CALL PROIN(XI(2),XI(3),XI(6),ANG(3),XIP(3))
C
C   DETERMINE PRINCIPAL MOMENTS AND AXES OF INERTIA.
C   THE IMSL SUBROUTINE EIGRS IS CALLED TO SOLVE THE
C   INERTIA TENSOR FOR ITS EIGENVALUES (PRINCIPAL MOMENTS)
C   AND EIGENVECTORS (PRINCIPAL AXES).
C
      XIT(2)=XIP(1)
      XIT(3)=XI(2)
      XIT(4)=XIP(2)
      XIT(5)=XIP(3)
      XIT(6)=XI(3)
C
      CALL EIGRS(XIT,IO,IOPT,EIGNVL,EIGNVR,IO,WK,IER)
```

```
C
C     PRINT THE RESULTS.
C
      IF(LL.GT.1)GO TO 575
      WRITE(16,550)HHEAD,IHNO,AMASS(1),ANG,COA,(COG(1,K),K=1,3),
     2  (T(1,J),J=1,6)
  550 FORMAT(1X,20('-'),'INPUT DATA--HOLDER',20('-')//1X,30A1/
     2  ' HOLDER #--',T25,I1/' HOLDER MASS--',T20,F7.3,T30,'KG'/
     3  ' ANG(1)--',T20,F7.5,T30,'RADIANS'/
     4  ' ANG(2)--',T20,F7.5,T30,'RADIANS'/
     5  ' ANG(3)--',T20,F7.5,T30,'RADIANS'//
     6  ' PT A COORD--',T20,3F10.4,' METERS'/
     7  ' HOLDER CM COORD--',T20,3F10.4,' METERS (W/O HB)'//
     8  ' PERIODS--',T20,6F10.4,' SECONDS'//)
  575 WRITE(16,600)SHEAD,ISNO,LCNO,AMASS(2),(COG(2,K),K=1,3),
     2  (T(2,J),J=1,6)
  600 FORMAT(//1X,19('-'),'INPUT DATA--COMPOSITE',18('-')//1X,30A1/
     2  ' PACK #--',T25,I1/' LOADING COND. #--',T25,I1/
     3  ' COMPOSITE MASS--',T20,F7.3,T30,'KG'//
     4  ' COMPOSITE CM COORD--',T20,3F10.4,' METERS (W/O HB)'//
     5  ' PERIODS--',T20,6F10.4,' SECONDS'//)
C
      WRITE(17,650)SHEAD,AMASS(3),(COT(3,1,K),K=1,3),XI,(XI(J),J=1,3),
     2  XIP
  650 FORMAT(1X,70('-')//1X,T20,30A1//
     2  ' MASS (KG)',T20,F10.3/
     3  ' CENTER OF MASS (M)',T20,3F10.3//
     4  ' MOMENTS OF INERTIA',T20,6F10.5//
     5  ' INERTIA TENSOR',T25,'IXX',T35,'IYY',T45,'IZZ',T55,'IXY',
     6  T65,'IXZ',T75,'IYZ'/1X,T20,6F10.5)
C
      WRITE(17,700)EIGNVL,((EIGNVR(JJ,KK),JJ=1,3),KK=1,3)
  700 FORMAT(///' PRINCIPAL MOMENTS OF INERTIA'//
     2  T25,'I1',T35,'I2',T45,'I3'/
     3  1X,T20,3F10.5///' PRINCIPAL AXES OF INERTIA (DIR. COSINES)'//
     4  3(T20,3F10.5/1X)///)
      WRITE(17,750)WK(1),IER
  750 FORMAT(' WK--',F7.3,'    IER--',I3)
C
  999 CONTINUE
      STOP
      END
```

```
C
C-----------------------------------------------------------------------
C
      SUBROUTINE MCMIN (AMC,DC,T1,T2,AMH,DH,DS,X1)
C
C
      PI=4.*ATAN(1.)
      G=9.81
      A=AMC*G*DC*T1*T1
      B=4.*PI*PI
      C=AMH*G*DH*T2*T2
      D=AMC-AMH
      E=D*DS*DS
      X1=(A-C)/B-E
C
C
      RETURN
      END
C
C
C-----------------------------------------------------------------------
C
      SUBROUTINE PROIN (P,Q,R,PHI,X2)
C
C
      A=TAN(PHI)
      B=A*A
      C=P+Q*B-R*(1+B)
      D=2.*A
      X2=C/D
C
C
      RETURN
      END
C
C
/*INCLUDE CAM02.EIGRS1
/*INCLUDE CAM02.EIGRS2
//DATA.FT16F001 DD UNIT=BAT,FILES=($OSC1,$OSC2)
//DATA.FT17F001 DD UNIT=BAT,FILES=($OSC3,$OSC4)
//DATA.INPUT DD *
/*INCLUDE CAM02.OSCDAT
/*
09350
```